A LUNAR

MINING VEHICLE

Proposed to:
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"Where there is much desire to learn, there of necessity will be much arguing, much writing, many opinions; for opinion in good men is but knowledge in the making."

— John Milton

<u>Aeropagitica</u>

ABSTRACT

Because of the exorbitant cost of shipping material from the earth to the moon and the probability of the colonization and industrialization on its surface, it will become necessary to mine the lunar landscape for construction materials. Design considerations for such a system must include the production constraint of mining 3.76 million metric tons of raw lunar soil per year. In addition to this constraint are those which take into account the harsh lunar atmosphere.

Assuming a lunar base and several communications satellites in lunar orbit have already been established, a roving, unmanned, mining vehicle that performs partial beneficiation in transit will be outlined in our report.

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I. INTRODUCTION

With the establishment and subsequent operation of NASA's space station of the 1990's, we will, as a civilization, have an important foothold in space. This will allow us significantly easier access to the planets surrounding earth and to our nearest heavenly neighbor, the moon. It is obvious, through the previous manned and unmanned expeditions to the lunar surface, that a plethora of valuable raw materials exist which would be most valuable to the space station's further structural augmentation, as well as for its life support needs. Procurement of each commodity directly from the earth will be both costly and inefficient; a much better solution will undoubtedly involve mining the moon's surface, processing the gathered soil, and shipping it to the space station for use.

As the base on the moon is developed to facilitate the mining operation, indigent raw materials will most likely be the ideal choice for most of its building needs. Elemental iron, silicon, titanium, and aluminum should be accessible following proper beneficiation of the raw lunar ore. Oxygen, which is of course necessary for life-support in alien environments, will of course be a by-product of the ore reduction processes.

Two ores, ilmenite and anorthite, can be readily separated from the lunar soil. The ilmenite, high in iron and titanium, can be concentrated up to about 90% and would comprise about 5-10% of the actual soil mined [1]. An anorthite concentrate of 95% and comprising about 45% of the soil would be likely to supply large amounts of Al and Si [1]. The beneficiation of the anorthite, to be carried out at the lunar base or in a space station in low orbit around the moon, would probably be achieved by carbochlorination followed with Alcoa electrolysis of chlorides [2]. The ilmenite would most likely be carbochlorinated and reduced by calcium to produce titanium dioxide [2]. Carbon monoxide from both metal extraction processes could be converted to methane or solid-state electrolysis could be used to generate oxygen from a gas mixture of carbon dioxide, carbon monoxide, and water [2].

Only partial mass reduction will be handled by the mining vehicle described in this report; further beneficiation will occur at a refinement center within the lunar habitat complex. This document will primarily delineate the operating details of the vehicle which will dig the surface soil, and reject approximately 80% of the dig. This will yield a concentrate which can then be returned to the habitat for final processing.

II. BACKGROUND ON ENVIRONMENT

The environmental conditions on the moon are immediate and dynamic considerations when designing anything for the lunar surface that will be exposed to these conditions. Gravity, diurnal cycle, atmosphere, and distance all have their effects on a project located on the moon.

The smaller size of the moon creates an acceleration of gravity which is about one-sixth that of the earth. This reduction in weight has direct effects on traction, which is reduced along with the weight, and energy requirements, which go down because less normal force is exerted on the vehicle.

The day/night cycle on the moon is 28 days long, during which the surface temperature varies between -120°C and +120°C. Since shadows are absolute on the moon, this cycle directly affects operating conditions and times. Materials are limited to those which can withstand these extremes.

The absence of atmosphere on the moon compounds the temperature extremes and the harshness of the lighting, which makes optical systems more difficult to use in the lunar environment. This vacuum also prevents the use of lubricants on the moon, limiting the use of hydraulics and linkages. Sealing bearings or lubricating them with solids becomes a necessity.

The distance to the moon is the most economically limiting factor in design work. At $15,000 per pound, utilization of materials already on the moon is a necessary consideration. Mining the moon will be an immediate necessity once any lunar construction begins.

III. ORE SEPARATION/BENEFICIATION

VOLUME ESTIMATION

The beneficiation processes performed on the mining vehicle as it collects soil are dependent on how much material is collected by the vehicle's scooper/drivers. Based on the estimate that 3.76×10^6 metric tons of soil would need to be collected annually to have a cost effective program, a collection rate of 856 metric tons per hour was calculated. Further calculations which follow in Appendix B show that this much soil can be collected using four trucks that travel 0.17 km/hour, with each truck collecting 214 metric tons per hour.

PROCESS

In the processing of ilmenite, it has been suggested that the best method would be the use of two electrostatic separators along with a magnetic separator [1]. This method is most often used in terrestrial industrial applications at present. The material must be sized to a value below 1mm using a 20 mesh screen, and those particles below the 200 mesh size must also be removed because they are too small to be effectively directed by electrostatic forces. The material would then be passed through an electrostatic separating device, a magnetic separator, and finally another electrostatic separator. Many different types of electrostatic and magnetic separating devices were investigated before a final design decision was made for this application. Electrostatic separation processes which were studied are corona electrification, inductive charging, triboelectrification (which includes frictional electrification), and fluidized electrification. The magnetic processes studied included low-intensity devices such as belt and drum separators, high-intensity devices such as the induced roll separator, and high-gradient magnetic separators.

ELECTROSTATIC SEPARATORS

Corona charging is most often used to separate conductive from non-conductive particles by charging all particles with the same polarity by ionic bombardment from a corona glow region [3]. The conductive particles are then neutralized by an earthed surface and a separation is possible [3]. Charging by corona discharge requires very expensive equipment to produce the required voltage and, also, selective deflection of particular fractions is difficult to achieve [4]. This method was not chosen for the lunar separation because the process involves fractions with differences much more definitive than simply conductor vs. non-conductor.

With inductance charging a considerable advantage is that most of the energy required for the process is spent in mechanically removing the particle from the electric field [3]. If properly designed, an inductive separator can be made to require no electrical power [3]. In the process, conductive particles become polarized into dipoles, are then attracted to an electrode, and are thus separated from the non-conductive particles [4]. Inductive charging works much better if one electrode is substantially larger than the other and if the particle stream is closer to one electrode [4]. In the lunar mining vehicle, this could cause a considerable amount of weight instability, and gravity is generally used to separate the particles from the electric field, This force in a micro-gravity environment like the moon might not be sufficient to effectively separate the materials from the electric field. Inductive charging was used in many early separation devices to separate wheat and grains, but other methods of charging particles of denser materials have been developed [4]. Also, inductive charging almost always inadvertently occurs along with triboelectrification, therefore, this process was not chosen as the sole means of electrostatic separation.

Triboelectrification is generally one of the most practical and least expensive methods of selectively charging particles for separation. Triboelectrification involves as the presence of charges after solid-to-solid contact has ceased [3]. Triboelectrification devices are usually vibrating conveyors with charged plates or large volume tanks with charged conveyor belts passing over the fluid surface to attract certain particles from the medium. The fluidized-bed process of separation was immediately rejected due to the almost complete vacuum conditions on the lunar surface. Any use of fluids for the entire lunar mining scheme has been rejected in order to avoid the complexity of airlocks and sophisticated control systems.

The vibratory conveyor concept was selected for the process due to the minimum of electrical and mechanical power necessary for each unit as enumerated in Appendix D. Also, this scheme has been used to efficiently separate ilmenite from beach sand in one pass through a vibrating table separator [4]. In a very gross comparison, the sand can be likened to the lunar soil with similar densities (2.14 g/cm^3 vs. 1.75 g/cm^3 for the lunar soil) and some of the same characteristics of high compressibility and cohesion. Thus, the vibratory conveyor with conductive and frictional charging was chosen for the lunar beneficiation scheme. The frictional charging of the process can be affected by humidity, temperature, dust, etc.; therefore, the lunar environment is considered almost perfect for electrostatic beneficiation because of its micropressure and low temperature conditions. Also, in the vibratory conveyor, the top plate, which is charged, must work against gravity to affect the particles, therefore the moon's gravitational force (one-sixth that of the earth's) will be another positive factor for this separation scheme.

The electrostatic separator will consist of a vibratory conveyor mechanism modeled by an existing industrial application built by Hapman Conveyors Division [5]. The vibrations are produced by a 2 to 7 hp motor drive connected to several evenly spaced metal springs. The metal springs were chosen over a type of polymer oscillator to avoid any problems of gaseous discharge. The pan of the vibratory conveyor which will form the lower electrode should be made of an insulating material with electrically conductive ribbing on the surface. The top plate or upper electrode should be approximately 5.72 to 7.62 cm above the lower plate. The vibrating deck is slightly sloped causing the particles to move toward the sides and end of the separator. The tailings will be discharged at the sides of the deck and the desired components will be collected at the far end of the separator and then fed directly into the magnetic separator.

MAGNETIC SEPARATORS

The concept of magnetic separation has been widely used in industry for many years beginning with the first separation of iron ores [6]. This separation involves the application of magnetic forces to attract the magnetically susceptible particles while other forces (frictional, gravitational, and inertial) pull the non-magnetic components in another direction, and thus separate the two fractions [7]. The magnetic concentrate (called mags), a non-magnetic component (known as tailings), and an intermediate fraction (called midlings) are produced. Magnetic separation is broadly divided into the two areas of low-intensity and high-intensity with induced pole devices.

The two primary types of low-intensity magnetic separation are belt separators and drum separators. These types of separators can only be applied to materials of high magnetic susceptibility. The belt separator is a device in which a conveyor belt is used to transport the material into an area with nonhomogeneous magnetic field [7]. The magnetic field is usually produced by a large, stationary electromagnet. A system of belts above the initial conveyor attracts the highly magnetic particles as they pass by and deposits in bins at the side of the main conveyor [6]. This method was not chosen primarily because of the uncertainty about the magnetic susceptibility of the lunar soil.

There are two kinds of low-intensity drum separators used commercially to separate iron ores: the dry and the wet separator. In a drum separator, the feed material is introduced at the top of a rotating drum and travels down along the roll by gravitational and frictional forces [7]. Stationary magnets within the roll produce magnetic forces which attract the magnetically susceptible particles and deposit these in a bin farther around the drum away from the non-magnetic particles [6]. Wet drum separators make use of hydrodynamic forces, produced by combining the feed material with a liquid, along with gravity and friction to separate particles smaller than those usually placed in a dry separator [7]. As in electrostatic beneficiation, any use of fluids is avoided, and thus the use of the wet drum separator was rejected. The dry drum separator was also rejected on the basis that the magnetic susceptibility of the lunar soil has not been determined. Therefore, it was determined that some type of high intensity magnetic separator should be used.

High-intensity separators can be used to effectively separate weakly magnetic particles if the magnetic field and magnetic gradient are both increased to account for the decreased susceptibility of the material [7]. The drum separator concept must be modified by creating a closed magnetic circuit. This is achieved by producing a rotating drum of laminar insulated discs made from mild steel and raising the edges of the roll to create a large gradient. In the induced roll separator (widely available on an industrial basis) the material is fed on to the top of the first roll, separated, and then passed to a second lower roll where the material is further separated [7]. In the high gradient magnetic separator weakly magnetic particles are separated from a slurry by using wire matrices to produce as large a magnetic gradient as possible [7]. Once again, the use of a slurry is not even considered for applications in the lunar environment.

For the lunar mining system a Carpco model MIH(13)231-100 magnetic separator was chosen to model the required separator [8]. This separator, based on the induced roll concept, actually contains four rotating drums giving an even higher degree of separation should be attainable from the weakly magnetic particles. The power consumption of the Carpco separator was also attractive at only 6.7kW [8]. Certainly considerable modifications would have to be made for use in this vehicle, most notably a decrease in the weight of the separator.

IV. MECHANICS

WHEEL SELECTION

The selection of the mode of traction on the moon's surface was narrowed to a choice between tractor treads and aluminum wheels. The basis for the decision took into account the properties of traction, deflection, and weight distribution. The outgassing property of rubbers on the moon eliminated any standard wheel types from consideration.

Tractor treads were eliminated from design considerations because of their poor translation to the conditions of the lunar environment. The support of the vehicle could be well designed in conjunction with treads running the entire length of the body, but this increased area of traction would reduce the concentration of weight of the vehicle on the soil. A second problem involves the linkages that would comprise the treads themselves. Lubrication would be required that would impossible in the near zero pressure of the moon.

Aluminum mesh wheels of the type designed for NASA for the Lunar Roving Vehicle were a logical alternative to the treads. Mesh wheels would themselves be very lightweight while having the the capacity to support 2000 pounds weight apiece. These wheels would allow for more deflection on the lunar surface and have better traction with the vehicles' weight concentrated on a smaller surface contact area.

Wheel design was furthered narrowed by the comparison of two wheel designs; open and closed mesh [9]. Both were designed to handle NASA's soil mechanics specifications, including an angle of repose value of 35 $\pm$ 4 degrees, for the lunar surface. The mesh wheel consisted of Armalon fabric sandwiched between two nylon meshes and anchored around an aluminum spring hub. This design performed the best of the two on loose soil slopes greater than 20 , but it required more power to operate to overcome elasticity, and the fabric incurred rips during operation. The open mesh design involves an aluminum mesh torus on an aluminum spring hub. Its increased reliability, flexibility, and traction made the open mesh the superior design.

SOIL MOVEMENT WITHIN VEHICLE

Two different methods are needed to move the soil within the Lunar Mining Vehicle; one for vertical lift and one for horizontal motion. Vertical lift is utilized immediately after the soil is collected by the scooper/driver.

As soon as soil is collected and sifted through screen the it is necessary to lift the material 4.5 meters to the top of vehicle so that the magnetic and electrostatic separation can work with the force of gravity. The bucket elevator designed to accomplish this has to work continuously to handle the constant influx of soil and without a chain loop which would require linkages and lubrication.

Development of this continuous belt type elevator was done using parameters set by the Continental Screw Conveyor Corporation [10]. The continuously welded buckets have flanged undersides, forming a chute down which each succeeding bucket can discharge. This allows for continuous discharge when operating at slow speeds. Rivets attaching the buckets to the belt should be in one horizontal row to allow for the flexibility needed when the belt pulls the bucket over the drive shaft.

A second belt drive elevator is needed at the rear of each vehicle to pick up the beneficiated material and dump it into a holding bin.

A method was needed for the continuous horizontal movement of the 20% of the material that remained after the beneficiation process. The ore would best be moved from the front of the vehicle to the rear bucket elevator by a screw auger.

Power and size requirements for the auger were obtained using screw model #10H306 made by Conveyors, Inc. [10] for the movement of ore. Parameters were specified for ilmenite ore and included a 15% conveyor loading capacity for ilmenite, a 16 in. screw diameter to handle the necessary volume of 866 ft/hr and a pitch diameter of 16 in. for the highest efficiency. Further specified dimensions for the screw are included in attached design figure. Using other specified parameters and formulas outlined in Appendix A, the conveyor speed was calculated to be 38 rpm and the total power required was 6.3 horsepower.

ANGLE OF ATTACK

In order to achieve the most efficient operation of the scooper\driver mechanism, the entire mechanism can be raised and lowered with a rack and pinion system attached to a pivoting arm connected to the front axle. In the raised position, the pinion is turned, forcing the rack up and the front axle down, raising the scooper\driver completely above the lunar surface so the vehicle can move and steer freely without digging. In the lowered position the pinion is turned in the opposite direction, lowering the scooper\driver to a depth of one-third meter into the soil. At this depth, the cross-sectional area that the two scooper\drivers will cover when excavating is 0.72 m [see figure 10].

The motive source for this pinion will be a servo-motor, the power for which comes from a generator connected into the flywheel mechanism.

In addition to these design choices, many other alternatives were considered for soil collection by the lunar mining vehicle. One of the first designs considered for soil collection was a modification on a front-loading vehicle. A scoop out in front of the vehicle would be forced into the soil and the vehicle would be pulled toward the scoop, forcing the soil into a catcher\bin between them. This was a viable design in that the forward motion of the vehicle was incorporated in the method of soil collection. It was discounted as not being a smooth, continuous operation.

Another consideration involved a paddle-wheel type drive. The wheel at the rear of the vehicle would bite into the soil, picking up soil in the paddle scoops and pushing the miner forward. The soil would be collected in a bin directly in front of the wheel as it was dumped off by each of the paddles. This design would have good traction, but a great deal of dust would be kicked up and rocks hitting the paddles would inhibit soil collection.

SCOOPER/DRIVER

The Scooper/Driver assembly located at the frontmost part of the lunar mining vehicle is a dual purpose apparatus. One purpose of the Scooper/Driver assembly is, as the name implies, a mechanism which will help propel the vehicle. The Scooper/Driver assembly has a center line axis positioned at a 45° angle with respect to the center line of the vehicle's main body (Fig. 2). When the assembly is given a forward rotation, the assembly has a tendency to roll off center. A support structure, located at the front of the assembly, prevents this action from occurring by tying the center shaft together. This action against action effect causes the assembly to dig into the lunar surface and pull the vehicle along a forward path. This is an extremely important characteristic of the assembly due to the low gravity of the lunar environment. Other traction devices, such as simple wheels or tracks, might slip on the lunar surface. The Scooper/Driver assembly takes advantage of its pulling effect to help propel the vehicle.

A second feature of the Scooper/Driver assembly uses the digging effect to move material from the lunar surface into the vehicle. The assembly consists of two layers, the solid outside layer and a 1.0 cm. mesh inside layer. A single internal thread, which spirals the length of the assembly, is used to support the two layers as well as move the lunar soil across the assembly.

The thread is connected to the center shaft by support rods positioned every 90° as viewed from the rear. The solid outside layer of the assembly is attached to the outside of the thread. The assembly is driven by a bevel gear located at the rearmost position of each Scooper/Driver. The bevel gears are connected to the Scooper/Driver differential which can be engaged and disengaged for mining or cruising respectively.

The net effect of the Scooper is thus: When the Scooper/Driver is engaged with the flywheel a rotation about its centerline shaft is caused. This rotation causes the Assembly to dig into the lunar soil. The internal thread picks up and carries the soil the length of the assembly across the top of the 1.0 cm. mesh screen.

As the soil transverses the assembly, the small particles of soil fall through the screen and get trapped between the inside layer and outside layer of the assembly, whereas, the large particles of soil stay on top of the screen. When the soil reaches the rear of the assembly one of two routes can be taken. The larger sized portions of the soil, the ones that stayed on top of the mesh screen, will be shoved out an opening through the back of the assembly and deposited overboard by a shoot. The smaller sized portions of the soil, which are trapped between the two layers, will fall through an opening in the outside layer. This soil will then be carried inside the vehicle's main body by a system of conveyer belts for further processing.

The design of the Scooper/Driver assembly is based only on theory. Its exact ability to function in a lunar environment is unknown. Consequently, improvements can be made through accurate model testing (which is beyond the scope of this course).

V. VISUAL SYSTEMS AND CONTROLS

INTERFACE BETWEEN TELEOPERATOR AND PHYSICAL SYSTEM

The need for human operators in the vehicle is overshadowed by the complexity in adapting man to such a hostile environment. Man must be equipped with life supports; a tolerable atmospheric and thermal environment must be present. The hardware and electronics involved simply to maintain a suitable environment for the operator implicates added weight, need for waste and heat dissipation, and added power consumption. An alternative is to have the operators onboard, yet in spacesuits. In this instance, human perception (as in peripheral vision) and physical response (due to the bulkiness of the suit) are severely limited. The onboard operator would be unable to perform several functions simultaneously, so the need for preprogrammed functions is realized. The operator in the harsh environment is additionally limited by fatigue and can operate less consistently and continuously than a preprogrammed machine. When subjected to fatigue, judgment may be impaired and indecision of the operator can put definite limits on the efficiency of the system. The harsh lighting on the moon's surface can lead to eye strain and can also limit the time element involved for adequate operation. Although benefits exist for incorporating onboard operators such as (accessibility to vehicle in case of immediate operational problems), a lunar mining machine with preprogrammed operations, relaying the status of those electronics, is the more desirable alternative.

The visual systems act as an interface between man and machine, and with teleoperations, an extension of man into hostile environments is possible. The human teleoperator is the core element in the feedback process and exists as a human transfer function; knowing a desired response, the operator can model the existing system to compensate for error and can back track to determine the proper system input. For the lunar mining vehicle, a closed-loop feedback system is mandatory, even if the vehicle is preprogrammed. A preprogrammed system is helpful in situations where time delays due to human response is a problem (as is the case with the vehicle: actual human operation is a problem due to reaction delay, life supports, and fatigue in the harsh environment).

Autonomy of the vehicle, however, is virtually impossible due to the complexity of the system and the concurrent expense. The artificial intelligence aspect, the decision making by the machine itself, could not be developed enough to combat the complexity of the lunar mining process (decisions on the ingestion rates of material, benefication procedures, compensation). It would then not only be required to see, but to decipher the information provided and to act accordingly. Supervisory control, the use of computers on the operator's end to aid in decision making and at the actuator end for adaptive control, is suggested in place of complete autonomy. A remote human operator is vital to determining the restorative processes required in maintainence. Humans are more equipped to improvise in analyzing the solutions to maintainence problems. Figures of merits and performance parameters are important in assessing the system: speed (is it controllable and adequate with existing power restrictions?), articulateness (each degree of freedom complicates the control system), cost, compliance (match of the interface), reliability (will the system function at some stipulated condition for a predetermined time?), and power requirements, among other parameters.

The operator should determine the optimal path and procedure for realizing the goal and should minimize any deviation, error (overshoot and undershoot).

When relaying information to the system from the operator and vice-versa, all redundant information should be dismissed to ease in data storage and transmission. The amount of information available for transmission is limited, and the manner of execution is similar to that in the human brain, where procedure dominates and circumstances are forgotten to make room for valuable input.

Commands [Fig. 13] usually take the form of electrical stimuli where they are then transduced and manipulated to produce mechanical output and back again to provide an assessment of the situation feedback. As an example, a servomotor may be preprogrammed to move a component a predetermined distance. An electronic timer can be employed to decrement and terminate the positioning process. Speed sensors are employed to measure translational and rotational movements of the motors and various components of the vehicle. Counting may be used with incremental encoders. A photoconductor detects variations in the motion of a disk attatched to a servomotor shaft. On the disk itself are black lines, equally spaced. The alternating optical signal can be transduced into electrical impulses, with the frequency of a series of impulses being the number of impulses per revolution times the speed of rotation of the shaft. This information is stored and analyzed in the computer and relayed to the operator. The operator then inputs a command for compensation and this can be accomplished through the use of inputting numbers that are transmitted and transduced by the vehicle's convertors into binaries for some switching procedures necessary for changing the response of the actuator end. The entire loop system for a servomotor to\from a load to\from the teleoperator is contained in the appendix [Fig. 13]. An all-purpose computer handles storage of information, timing, analog-to-digital conversion and vice-versa, and provides the output interface to peripherals. From digital-to-analog, the signal is amplified for input to the servomotor. The motor acts as the interface between electrical and mechanical systems. The major obstacle with the incremental encoders is that the photoconductor/disk subsystem requires a light source. Furthermore, at very low speeds, the incremental encoders are unstable. For this reason, a tachometer with AC supply is more suitable for the remote speed sensing. Its information is relayed to the computer and converted from analog to digital form, which is in the proper form for computer analysis and data transmission.

With these logic schematics from the appendix, the process of input/output for the lunar miner is determined.

VISUAL SYSTEMS

The operator is limited by his remoteness; a visual system is mandatory for assessment of the situation. The teleoperator is to be guided across this barrier with the aid of two-way communication links, sensors, and feedback control systems. One methodology suggests a series of potentiometers to relay a electrical impulses when a certain function has been performed and terminated. A more sophisticated sensing system such as a visual one should be employed so that if any unpredicted obstacles arise, another course of action can be implemented from operator to actuator. Potentiometers are helpful when connected to mirrors and filters to monitor movement. With a cybernetic system (preprogrammed), the sensors act as backup systems. The actuator subsystem of the visual system will entail the image sensor and positioning and monitoring components. The control subsystem will include the human operator to compare data and make operational corrections.

The typical robotic visual systems are the following: a light source (drawbacks: the light source from the sun causes sensitivity to high-intensity light), image sensor (drawback: limited depth perception, limited resolution, thermal instability of the environment), image digitizer, feature extractor\data compactor, system control computer, output and peripherals. [Fig. 13].

Although the typical image sensor utilized is a vidicon tube, charge coupled devices have been found to be more resilient to shock, smaller, and have greater sensitivity. Charge coupled devices work well in very low light and are good in bright light; the image typically is not burned onto the photosensitive component. The entire video package is smaller than with a vidicon, so less inertia exists when going through dynamic loadings. This fact reduces the need for compensation. Charge coupled devices (CCD) consist of solid state silicon image sensor array (a grid of semiconductors on an integrated circuit). They have successfully performed on the Galileo Jupiter Orbiter mission. In an imaging capacity, the CCD is accompanied by an electromagnetic focal plane shutter. The image digitizer is a fast, eight bit analog-to-digital converter that stores the image to be assessed by the general purpose onboard computer. With onboard data systems, the processing is limited by the video data because the high volume data is of a continuously changing nature. The feature extractor/data compactor relays pertinent information derived from inherent algorithms. It provides high speed processing of input image data and pattern recognition systems. If the vehicle were completely autonomous, the pattern recognition is a must, for it is important that the machine, say under dynamic loading or its camera abnormally positioned, realize the "sameness" or difference of the image, regardless of the window taken. The inherent degree of difficulty required for this task makes the image sensor relay to a teleoperator a more desirable alternative. Furthermore, with autonomy, the visual system must decide to re-orient and translate itself until it achieves a recognizable pattern. (Example: cameras encounter complete darkness, and terminates the translation by noting the differences in gray levels).

The television system should also be capable of receiving, decoding, and implementing certain commands from the operator: rotating filter wheel, changing focus, or repositioning the camera orientation.

Depth perception is a necessary condition because the vehicle will encounter unforseen craters, and it must be able to distinguish distances to obstacles. Two cameras should be utilized for depth perception, but a problem of added weight is encountered. The secondary camera, though, acts as an inherent backup system. [Fig.13] One camera could be utilized, and continuous motion in the z-direction to give the proper perception is a possibility. Problems arise due to redundancy; the camera is reiterating previously photographed images. Another imposed difficulty is the computer must recall the exact position for superposition on the raster scan. (A raster scan is the way in which images are relayed to, say, a television console, by use of a predetermined positioning of binaries onto the screen. The binary digits may indicate the proper brightness, black/white/gray levels). One proposed but eliminated alternative is that each camera is stationary relative to the other, but if one side of the vehicle were to elevate at a different time than the other or not at all, then the scan would not superimpose properly. Compensation and dampers would then be required, so attitude is adjusted to maintain a predescribed level. Referring to Fig. 14, the cameras should be allowed to translate along the y-axis so as to be positioned, with servomotors, to see directly in front of the vehicle and beyond. A system could be employed such that the actions of the cameras could be closely coupled with the operator's head and a system used to detect eye motions for finer control and resolution. The system would then follow the actions of certain parts of the operator's body [Fig. 13].

To visualize the rear of the vehicle, the cameras could rotate about the z-axis, but upon making the 180 degrees of revolution, the camera would essentially be upside down and either operator or the camera must be able to analyze the image correctly. To avoid this process, both cameras will be able to rotate 360 degrees about the y-axis. Planar mirrors positioned on top of the flywheel container and another attatched to the side of the rear panel should provide adequate vision in the rear for the coupling procedure with the ore transport. The cameras should be positioned parallel to each other. In dealing with extended distances, the human eyes are essentially parallel, and are cross-eyed for only a very short distance close to the viewer. A proper aperature and a wide field of view are necessary to produce clear images from ranges of one-tenth of a meter to about 100 meters away.

Calibration of the cameras is important, because (as on the Voyager mission) when images are stored on a photoconductor, a nonuniform scan array is generated. The resulting photographs from Voyager were geometrically distorted, and to correct this, a subsystem of metallic dots (reseau marks, a specified distance from one another) remain on the photographs. If they are distorted, the degree of distortion of the dots indicates the degree of distortion of the photographs. During the Voyager mission, focusing was accomplished by concentrating on the

Pleiades constellation and the lenses' exact focal length was determined with knowledge of the distance between Voyager and the constellation. Some sort of calibration for the lunar mining vehicle could assimilate this process, such as focusing on a known landmark on the surface.

Temperature is a major consideration with regard to the cameras' lens plates. Plastic cannot be used to protect, due to the fact the ultraviolet rays can degrade their performance and destroy the plastic. A radiation shield must be used, one that will not falter in the presence of the extreme thermal stresses, pitting, and deposits of dust and metallic deposits. Putting some sort of electronic charge such as deposited ions could deter this action. In addition to this charge, positioning the cameras up and away from the main body of the vehicle should aid in alleviating the dust accumulation on the lenses. (Since in an absolute environment and experiencing only one-sixth the gravity of earth, the dust particles should follow essentially a trajectory pattern, peaking at some height, depending on the speed, weight of the particle, etc.). A heater will be employed to protect the temperature sensitive elements and will be automatically controlled and activated if a minimum temperature requirement is surpassed. In the past, thin coatings have been applied to the lens systems to reduce the effects of pittings and thermal stresses leading to optical degradation. Typically used coatings are metalized second surface mirrors such as Kapton, Teflon, and quartz. Aluminized Teflon had adequate solar absorptivity and emissivity [based on a study by Andres, Blair, and Smith with Hughes Aircraft Co. in Culver City, CA] for a three year exposure. During the ten year exposure samples, surface cracking was noted, but not on samples of white paints, certain metals, and black paints. Vapor deposited aluminum on Kapton seems a good candidate for coating optical lenses. Most materials for television camera lenses, along with most optical components are crystalline and amorphous ceramics. But ceramics contain inherent voids, causing dislocations to propogate and ultimately to cause failure. Furthermore, ceramics are strong in compression, but weak and brittle in tension; this fact could pose problems when the camera subsystem is experiencing dynamic loading. Typical materials for lens sybsystems are included in the following: flint glasses, cerium-stabilized glass, or fused quartz. Ordinary glass is most susceptible to damage, fused silica and synthetic quartz are next followed by quartz as being the least affected. Although rare, different thicknesses of quartz could be employed on the optical components to reduce degradation. Aluminosilicate is very susceptible to surface pitting from protons and is therefore not a good candidate for an optical coating.

The charge coupled device itself, to minimize image data degradation due to charged particle attack, will employ a one centimeter thick tantalum shield in addition to the ionizing depositing mechanism. The shield will not cover the image exposure aperature. The CCD will be located within the structure for the camera and is removed from surfaces in contact with the harsh environment. To dissipate heat, a heat pipe must be used as an interface between the electronics and the outside environment. (A heat pipe is simply a heat transfer device with a high thermal conductivity which acts as a radiator). A heat pipe is inherently simple in operation and it has no moving parts; its purpose is to maintain near isothermal conditions. The evaporator of the flexible heat pipe is mounted to the electronics. The heat from the electronics vaporizes the working fluid in the evaporator. The condenser length is next to a flat plate metal. At this point, the desirable situation is to have a material that has a low solar absorptivity, but a high emittance (infrared). This flat plate acts as a second surface mirror (it reflects incoming solar radiation and reflects the infrared radiation). The video electronics are insulated and coolant enters and exits about the electronics and insulation. The heat pipe condenser will be surrounded by a twopass, annular heat exchanger. For increased efficiency, the flat plate radiator can be angled parallel to the solar vector, thereby minimizing the absorptivity. Instead of flush-mounting this plate, the plate should be oriented as in Fig. 13. The area is doubled and consequently, the heat transfer is doubled.

Finally, the performance parameters of the charge coupled devices are assessed in Fig. 13. The CCD used for the Galileo Jupiter Orbiter mission was 800 active lines per frame and 800 pixels per line. The word length depends on the number of gray levels desired. Complete images are incorporated into the single-bit-at-a-time transmission rate. To give an indication of possible values, video monochrome (black and white) has an aspect ratio of three-fourths and each frame has two fields, and each frame is made of 525 scan lines. Each field is drawn on every other scan line every one-sixtieth of a second, and then the next field is drawn on the remaining lines.

LASERS

Lasers have been implicated as a source of power transmission. The benefits of utilizing lasers as opposed to other systems are as follows:

-Directly solar pumped (pumping is a process in which electrons are excited to an upper energy state whereby more electrons are located in the upper than lower state inducing instability; the transitions to lowest energy state, simply, will result in lasing action (stimulated emission)). The direct solar pumped system implies no replenishing of pump source and power supply.

-Lasers systems are four times smaller than microwave systems, for transmitting the same amount of power. (The consensus is for relaying through a satellite system from the teleoperator).

-Lasers have inherently small beam divergence (beam spread) and have good collimating capacities. Most have a small wavelength. All the predescribed characteristics are ideal for remote energy transmission.

-Since lasers are essentially monochromatic and coherent, communications signals are not distorted (as in random spontaneous light) and are thereby easily directed and detected.

A good candidate for the type of laser is the indirect blackbody solar pumped laser for its efficiency. Blackbody radiation is used to excite and pump carbon dioxide. A carbon dioxide system yields a high-powered laser, used in machining processes such as metal cutting. The directly solar pumped CFI 37 laser is produced through the absorption of solar radiation. This pumping mechanism indicates fewest conversion steps from sunlight to electrical power. The optical efficiency is low, but the overall efficiency is higher due to less components involved. Nuclear pumped lasers are infeasible due to the disadvantage of a required gas core reactor that would add excess weight and maintainability. A predominant problem with using lasers is the high threshold requirement for continuous lasing. High threshold implies instability and difficulty of maintaining lasing action. Furthermore, depopulation (the process of reducing the number of electrons present in the upper state) hinders lasing and occurs due to the increase in the triple state density (the level is saturated with energy and does not want to relinquish it) causing no lasing action. This activity is particulary prevalent in the dye lasers, which are liquid lasers that have an active medium of an organic dye dissolved in a solvent. The advantages of this laser over the doped insulator lasers (whose active medium is a regular array of atoms) is that inhomogeneities in the doped insulator's crystal structure can greatly degrade its coherence. The dye laser does not display this problem.

High data-rate communications are possible with lasers (a typical value is five million bits per second for continuous television). Required power levels for maintaining these lasers, over a distance to Pluto from earth with a one meter diameter transmitter and ten meter receiver, are as follows:

-Carbon dioxide laser: 2 kW

-Visible laser: 100 kW

Source: p. 20, Jones and Young. A High-Power Space-Based Laser Researcn and Applications Program, NASA, Washington, D. C., 1983.

To beam a power level of 100 kW, the required collector diameter and mass is forty- two meters and 10,000 kg, in assuming some orbital position with regard to the moon. These large structures are inherently unstable. (These figures are consistent with the solar-pumped laser satellite system depicted in Fig. 15, p. 18, Jones and Young.

The instability of the lasers reduces their reliability. Maintaining satellites and creating the hardware are all economic factors that could be reduced simply by using onboard power generation. Positioning the remote laser to connect with the collectors of the continously moving vehicle would be difficult to achieve and maintain. Another limiting factor is the added weight of the collectors and their size. Even though there is small beam divergence, over extended distances, the beam's diameter can become many times the initial, implicating a large collector. Similary, if the transmission were to be from a remote lunar position, similar problems would occur. An alternate means of power transmission, based on this analysis, must be determined. (Laser propulsion systems, the process of physically moving a vehicle by use of a laser, is a possibility).

VI. POWER TRAIN

POWER REQUIREMENTS

The power required for the miner comes from several subsystems: the digging process itself, rolling resistance of the machine, inertial forces at startup, the conveyors and augers that lift and move the soil in the machine, the beneficiation process consisting of electrostatic and magnetic separation, and miscellaneous electrical requirements. These subsystems will be considered individually with respect to their power requirements.

The power required by the digging process is extremely difficult to estimate. Because of the complex parameters involved in soil mechanics and the complicated geometry of the digging cups, any sort of analytical estimate is nearly impossible. The optimum method of determining digging power would be to build a scale model with "scale soil" and use dimensional analysis to find power requirements for the prototype. Since this is out of the scope of this project, the only alternative is to examine terrestrial excavation machinery and attempt to relate engine horsepower on these machines to power necessary on a lunar mining machine, keeping in mind differences in soil and power necessary for lifting the soil. The method used sets up a proportion based on speed of forward progress and cross-sectional area of the dug soil to find an order-of-magnitude approximation for power (See Figure 10). Perhaps the earth machine closest to the lunar digger is a trencher, a device which digs a relatively small linear trench for cable and pipe installation. Several such machines were examined through the vendor catalogs. The best example was the Ditch Witch combo, which has four models ranging in power from 30 to 65 hp [11]. Based on such comparisons, we established the power required for digging at the normal speed of 0.2 km/h to be on the order of 40 hp.

The power used in overcoming rolling resistance should not contribute greatly to the overall power requirement because of the very slow speed at which the digger proceeds during digging. With the digging apparatus disengaged, however, the machine should be able to move significantly faster, but power required for this should not exceed that for digging. Consequently, rolling resistance has been neglected. The same argument can be used to neglect the power due to inertial (start-up) forces.

There are also electrical requirements for the various motors, communications and control systems on board. The largest user of electrical power, however, is the beneficiation process. The power requirements for the magnetic separation process are given in the vendor catalog as 6.7 kW [8]. The electrostatic separator is still in the developmental stage, so power measurements have not yet been carefully determined, but the power needed can be estimated to be also about 6.7 kW [8].

CHOICE OF POWER SOURCE

The choice of a power source becomes an enormous problem for a mobile land vehicle on the moon. Any sort of chemical fuel must be immediately ruled out because of the tremendous cost of shipping fuel from earth. Unfortunately, chemical fuel gives the best energy density (usable energy per unit mass) available [12], which is of course very important for vehicular applications. Power sources that might conceivably work for the miner were determined to be: photovoltaic, "conventional" storage cell, fuel cell, non-cyclic heat engine, laser transmission, and flywheel.

Photovoltaic power might initially seem to be a reasonable power source by taking advantage of the virtually 100% unattenuated beam radiation that the lunar surface receives from the sun. However, the energy flux is still relatively low compared to other forms of power, and the solar panels required would be very large and very heavy, an obvious drawback for a mobile vehicle.

Reversible chemical cells, also known as storage or secondary cells, have made steady technological progress in recent years. Today they are used on a limited basis to power such urban vehicles as commuter cars and delivery trucks, with a range on the order of 100 miles. Their main drawback is their low energy density, requiring very heavy batteries for relatively modest power requirements [13]. Fuel cells have a much higher energy density, and have the advantage of considerable previous use in space vehicles, including the lunar rover. As such, they could probably be used in the excavator. It must be remembered, however, that all chemical energy storage devices are exothermic when discharging [14], which can lead to significant thermal control problems for space applications.

The last three power sources considered are more unconventional. The non-cyclic heat engine is a concept that takes advantage of the large temperature differences occurring naturally on the moon, and the relative ease of thermal insulation. The engine is powered by small heat sources and sinks, contained in materials with very high specific heat. The source is heated by solar concentration to a very high temperature and stored in an insulated container until needed, and the sink is cooled by radiating its heat to space until it reaches the cryogenic temperature range. Thus a very large temperature difference is established. Before the vehicle leaves the base, the working fluid in the engine is heated to a high temperature and pressure and the hot and cold bricks are installed. Heat transfer fluid circulates between the hot bricks and the fluid, vaporizing it. The vapor passes through a turbine producing work, and condenses at a second heat exchanger containing fluid flowing from the cold bricks. The condensed fluid then flows to a holding tank. There are several apparent advantages to this process: because the process is noncyclic, it is not limited by the Second Law (Carnot efficiency). In addition, much of the energy in the fluid is already present since it is heated at the base, and the hot bricks need only provide the heat of vaporization and replenish thermal leakage losses.

The main difficulty with the non-cyclic heat engine is the problem of analyzing its performance. The process is entirely transient, and there are a very large number of variables to consider. A fairly sophisticated computer program would be needed to fully analyze the process, which was not available to the group. Also, it was believed that the size and weight of the source and sink would be at least as great as an electrical storage system. The idea was therefore dropped, although it may have possibilities for other space applications.

The concept of powering the machine by aiming a high-energy laser at a small array of photovoltaic cells on the machine is attractive because the power plant is not carried along with the machine. There are significant problems with aiming the laser, possibly by satellite, and the consequences of hitting an area of the machine other than the collector array. Although these problems may well be overcome with the current research in the Strategic Defense Initiative program, it was decided to discontinue this idea as a power source.

The last power supply considered, and the one eventually adopted, is the high-energy-density flywheel. Although used for centuries as "load levellers" and short-term, low-energy storage devices, advances in composite materials and bearings have made flywheels very attractive for a mobile power source. Advanced flywheel designs have efficiencies of close to 100% [15], energy densities far greater than fuel cells for space applications [16], and excellent power densities (peak power per unit mass) as well [12]. Flywheel storage has compared very favorably to fuel cells and nickel-hydrogen and nickel-cadmium storage cells for use on the space station [16].

Another advantage is that mechanical power is coupled directly, instead of having to be converted from electrical power in an electric motor. Flywheels also have a chargeup time an order of magnitude less than chemical cells, and can undergo many more charge-discharge cycles. Major disadvantages of flywheels include:

1. The need for a continuously variable transmission to couple the flywheel to the load, and bearings able to handle very high speeds with minimum drag.

2. Fatigue and vibration problems associated with the high speeds encountered [17].

However, these problems can be overcome and are not sufficient to eliminate flywheels as an energy source.

FLYWHEEL DESIGN

The energy density of a flywheel (useful energy stored per unit mass) is found as follows:

$$(e/m) = (a)(K)(s/w) \;/\; n \text{ , where}$$

e/m = energy density
n = velocity safety factor, or (breakup speed)/(maximum speed)
a = "depth of discharge factor," or ratio of useful to total energy stored.
K = geometric shape factor
s/w = strength to weight ratio of flywheel material

This equation is based on the assumption that the maximum energy of the flywheel will occur when the stress on the material equals the strength of the material divided by a safety factor [12]. To use the lowest mass possible, it is therefore desirable to optimize a, K, and s/w. The highest K value possible is unity and is obtained for an isostressed flywheel; that is, each point undergoes identical stresses. Since this configuration is thicker in the middle and tapers away from the axis [12], it has a relatively low moment of inertia for its weight and thus must spin at very high speeds to achieve the desired energy density. A perfect isostressed flywheel would have a peripheral velocity approaching infinity, but "realistic," nearly isostressed flywheels have K values ranging from 0.7 to 0.98. In actual practice, isostressed flywheels contain a flat outer rim which exerts a radial stress on the disc and increases its strength. To keep peripheral velocities low, the flywheel should be thick in the axial direction. In addition, there should not be a hole through the center of the flywheel, for this will double the maximum stress. To connect the disc to a shaft, short stub shafts are built into the flywheel at the center, where it can be attatched to a flange on the shaft [12] (See Figure 7).

Besides having good shape factors, isostressed flywheels have low gyroscopic moments compared to their weight [12]. This is particularly important in vehicular applications, since such a moment can cause major problems when turning the vehicle. Much of this problem can be eliminated by orienting the axis of the flywheel vertically, therefore eliminating the gyroscopic moment on the yaw (turning) axis. Although there could be problems when the vehicle with a vertical flywheel axis is on a slope, this orientation would aid in roll (tipping) stability.

The above equation also assumes isotropic material properties, and some of the best candidates for flywheel materials, namely the fiber composites, are highly anisotropic. However, most of the stresses occur in one direction (radially), and an effective strength may be used. There are many exotic materials with extremely high ultimate strength, ranging up to 21,000 MN/m for graphite whiskers, but most of these have had little or no application on flywheels to date. The most common material for high-technology flywheels is Kevlar, with a strength-to-weight ratio of 1700 kJ/kg [12].

The depth of discharge factor, a, is the ratio of the difference in kinetic energies of the flywheel at highest and lowest speeds to its kinetic energy at highest speed, and therefore is largely dependent on the transmission used. Often the lowest speed is about half the highest speed, giving an a value of 0.75 [12]. This can be used as a first approximation before a transmission is chosen.

With a power requirement target of 52 kw or 70 hp, the design of the flywheel may proceed. The following parameters are chosen:

K = 0.95
a = 0.75
n = 1.25
r = 1.5 m
Choose Kevlar (1700 kJ/kg) as material
Power Duration = 5 hours
Energy required = 940,000 kJ

Which results in the following values:

Energy density of 969 kJ/kg.
Mass of the flywheel = 970 kg
Rotational Speed = 1990 rad/s = 19,000 RPM
Width at Center = 32.7 cm

Also considered was a flywheel with a range of two hours, which had a mass of 388 kg. However, it was felt that this was an inadequate range, so the five-hour flywheel was chosen.

POWER TRAIN COMPONENTS

A flywheel-powered vehicle requires the following drive train components: flywheel, speed reducer, continuously variable transmission, and the more common elements such as shafts, bearings, clutches, differentials, bevel gears and universal joints [15]. All have special requirements and constraints due to the harsh working environment, which will be subsequently discussed.

Fortunately, the lunar vacuum improves flywheel performance in one respect by virtually eliminating aerodynamic drag. High-speed terrestrial flywheels are usually rotated in an evacuated chamber to reduce drag [12], but this need not be done here. The vacuum, however, eliminates the option of using liquid-lubricated bearings and requires that seals be implemented on devices such as transmissions and differentials. These concerns will be dealt with in more detail below.

SPEED REDUCERS

Since the flywheel rotates at very high speeds (on the order of 20,000 rpm) and the drive wheels and digging cups rotate quite slowly, a speed reducer or series of speed reducers with a very high reduction ratio, very high input speed, and high output torque is required. Although a cascaded system of reducers should provide a sufficient reduction ratio, problems associated with the high input rotational speeds are not easily solved. There appear to be few if any reduction units on the market that are capable of handling input speeds of 20,000 rpm, especially with the limitations on lubrication. Thus a high-input speed gear reducer appears to be a component that must be custom-designed for this project.

CONTINUOUSLY VARIABLE TRANSMISSION

There are several types of continuously variable transmissions (CVTs) on the market, including traction drive, hydraulic, hydrostatic and electrical, as well as hybrid split-flow devices [12]. In terms of efficiency and environmental considerations, the traction drive type appears to be the most suitable. Hydraulic and hydrostatic types suffer from extreme viscosity variation with temperature, and these as well as the electrical type generate excessive amounts of heat and exhibit relatively low efficiencies. A traction drive transmission was therefore chosen for the design.

Most modern traction drives operate with a special "traction fluid" between the various drive elements which lubricates the components. When a very high local pressure is exerted on the fluid, as in rolling contact between two members, the viscosity of the fluid increases dramatically, creating a tremendous shear stress which transfers the power flow and minimizes slip. Some models, in fact, have efficiencies as high as 95% [18]. Since the amount of fluid used in a traction drive is small, vacuum sealing problems are reduced and thermal control is much simpler than in other transmission types.

One drawback to traction drive transmissions is that there are relatively few models with a sufficient horsepower rating. Of the types researched, only the Kopp roller drive, Vadatec nutating cone, Beier disc variator and Excelermatic toroidal types had models with the required horsepower rating [18]. The 100-hp "A" type Beier variator or equivalent with a 4:1 reducer ratio appears well-suited for this application. It has a rated input speed of 875 RPM and an output speed varying between 68 and 271 RPM [19]. However, in a flywheel power system, the input speed to a CVT is constantly varying while the output speed and torque remain fairly constant (at the minimum output shaft speed). At maximum flywheel speed, the CVT input speed will be at its rated value of 875 RPM and maximum ratio, while at minimum speed the CVT ratio will be at its minimum value of 875/271 or 3.23:1, and input speed is (68 RPM) x (3.23) = 220 RPM. Therefore, additional reducers must be installed, both between the flywheel and transmission, and between the transmission and load. The rotational speed of the drive wheels is approximately 3.75 RPM, so the transmission-load reducer ratio must be 68/3.75 = 18:1. The flywheel-transmission reducer must have a ratio of approx. (19,000 RPM)/(875 RPM) or 21.7:1.

FLYWHEEL BEARINGS

As previously mentioned, special attention must be made to bearing choice in a vacuum application. Liquid lubricants will evaporate very quickly in a vacuum and thus require hermetic sealing as well as active thermal control, which adds weight and complexity to the system. Solid lubricants have very low vapor pressures, and their lubrication mechanisms are independent of ambient temperature and nearly independent of temperature in the design temperature range (-200 C to +200 C) [20]. This makes them ideal for space applications. Therefore, except for flywheel uses and heat transfer considerations, bearings used for the vehicle need not be radically different from terrestrial roller bearings except for the lubrication mechanism.

The choice of bearings for the flywheel is especially critical, primarily because of the very high rotational speeds. In particular, there is a significant thrust force on the vertical shaft due to the weight of the flywheel. There should also be as little drag as possible on the shaft which would degrade the flywheel energy and create significant heat dissipation. Because of these considerations, magnetic bearings appear to be the best choice for flywheel applications. Since there is no contact between solid surfaces, there is no wear, no lubrication needed, and drag torque is extremely low over a wide range of speeds [21]. In addition, they have very high reliability [22], maximum speeds which can approach flywheel stress limits [21], insensitivity to thermal conditions, high momentum capacity, and low induced vibration [22].

There are basically two types of magnetic bearings, active and passive. Active bearings use electromagnets and electronic control circuits, while passive bearings employ permanent magnets. Active bearings have the advantage that dynamic parameters such as stiffness and damping can be controlled. However, magnetic bearings are massive and bulky compared to normal bearings, and the active (controllable) types consume power [22]. There are many configurations of magnetic bearings, with varying numbers of degrees of freedom constrained by magnetic means. In simple systems, the thrust direction is restrained magnetically while the other four degrees of freedom are handled by more conventional means [12]. Because the thrust is by far the dominant force on the flywheel shaft bearings, a bearing with magnetic control in the thrust direction only may be satisfactory.

Even among all-magnetic bearings there is considerable design variation. There are repulsive and attractive permanent magnetic systems, but only the repulsive variety are stable. There cannot exist a stable, completely passive three-dimensional system; at least one axis of the suspension must employ an active servomechanism. This, however, entails a power drain [23], which is a prime reason for initially considering magnetic bearings. This is one argument in favor of using hybrid magnetic and lubricated bearings.

CLUTCHES

There are also several different types of clutches that may be considered on the vehicle, notably friction-contact clutches, hydrodynamic fluid clutches, and electromagmetic flux clutches. Friction clutches have the advantage of relative mechanical simplicity and zero slip during steady-state performance. Of the friction clutches, two in particular have been evaluated for spaceflight applications: wrap-spring and disc clutches. Wrap-spring clutches have faster response time, higher torque/weight and torque/volume ratios and much lower actuating power requirements than disc clutches, but suffer from significant drag torque and lower disengaging reliability than disc clutches. Disc clutches have little if any drag torque and thus have very modest thermal requirements, but must employ an electromagnetic or pneumatic engaging mechanism [24].

Fluid clutches do not seem well-suited for space use. They undergo constant slip and therefore require constant heat dissipation. In addition, they generally have low torque/weight and torque/volume ratios and have undpredictable torque output during high turbulence and slip [25]. Electromagnetic flux clutches, on the other hand, have several desirable features with regard to spaceflight. They generally have only one control parameter (coil current) and have smooth operation. The eddy-current clutch can transmit very large amounts of power, but since slippage must occur for torque transmission, there is significant heat dissipation. The magnetic-particle clutch has the advantage of maintaining constant torque even at 100% slip [26].

Heat rejection has been discussed peripherally above, but must be considered carefully in any space system. Since convection does not occur in a vacuum, conduction or radiation must be used. Conduction may be useful for light heat transfer applications such as bearings and friction clutches, but in general is probably inadequate for dissipation of large amounts of heat such as that generated in electric motors or transmissions. For these applications, probably a heat pipe network will be employed between the heat-producing components and exterior radiators. Since the effective radiation temperature of deep space is close to absolute zero, thermal radiation can be quite efficient on the moon. The tilt angle of the radiators should point away from the moon's surface and the sun as much as possible for maximum thermal efficiency of the radiators. If the radiator panels are located on the side of the vehicle and the vehicle's digging pattern is in the east-west direction, then the panels will never face directly into the sun and should radiate very effectively. However, this orientation would cause extreme difficulty with visual systems and is likely to be impractical as an absolute constraint.

LUNAR MINING VEHICLE PARTS LIST FOR FIGURE 2

ITEM NUMBER	DESCRIPTION	REFERENCE FIGURE #
1	SCOOPER/DRIVER	4,5,6
2	ALUMINUM OPEN MESH WHEELS	
3	FLYWHEEL	7
4	SPEED REDUCER	
5	RIGHT ANGLE DRIVE / CONTINUOUSLY VARIABLE TRANSMISSION	
6	REAR DIFFERENTIAL	
7	FRONT DIFFERENTIAL	12
8	DRIVE SHAFT	
9	SCOOPER/DRIVER DIFFERENTIAL	
10	SCOOPER/DRIVER DRIVE SHAFT	
11	SCOOPER/DRIVER SHAFT	
12	FLYWHEEL SHAFT	
13	GENERATOR	
14	FIRST BUCKET ELEVATOR	8
15	FIRST ELECTRO-STATIC SEPARATOR	
16	MAGNETIC SEPARATOR	
17	SECOND ELECTRO-STATIC SEPARATOR	11
18	SCREW CONVEYOR	9
19	SECOND BUCKET ELEVATOR	
20	[illegible] CHUTE	
21	[illegible]	
22	ON-BOARD COMPUTER / ELECTRONIC CONTROLS	13
23	LIGHTING	
24	STORAGE BATTERIES - NIGHT	

on materials with limited ductility by this method. It cannot be used in the instance of sharp contours and re-entrant corners). Cold welding can be a problem in the absolute environment; Ti-6Al-4V does not adhese easily to itself or other materials (copper and Al 2014 adhese to like and unlike materials in this environment. Dissimilar materials are more apt not to bond together, due to differences in the lattice structures). Dynamic loading reduces minimum bonding temperatures due to a smoother resulting surface. (Stainless steel bonds at room temperature. Strengths can be increased or reduced if a non-oxidizing atmosphere (some materials depend on oxidizing atmospheres for increased strength). A reduction in strength can be due to decreased surface energy accompanying gas absorption, thereby decreasing the work needed to induce crack propagation. Fatigue life does not noticeably change.

Spinning should be used in manufacturing the scooper/driver system. Its resulting stress state is similar to cold rolling and stretch forming. A problem with spinning is that the cracks could form at the outer edges, where biaxial stretching is most predominant. To alleviate the biaxial stresses, the direction of rolling should be as the same direction of curvature, but elongated inclusions are then induced in the material. These inclusions are more detrimental than the globular inclusions. The transverse ductility is reduced by anisotropy (nonuniform structuring of crystals due to voids); this implies an increase in brittleness and a reduction in resilience to dynamic loading and shock. A possible solution is to stretch form several sheets with some minimal degree of curvature and bolt them together.

This solution is more susceptible to losses due to leakage. (The process was used with panels of Al 2219-T851, which has high strength with good toughness. It also exhibits good behavior under biaxial stress). The Ti-6Al-4V is a good choice for the cold spinning process for the scooper/driver, due to its consistency at varying temperatures of the ultimate and yield strengths and increased ductility at the higher temperatures. The body-centered cubic structure of titanium is desireable for its increased ductility over the hcp structure which tends to be brittle and sensitive to stress corrosion.

In instances where thermal fatigue, shock and thermal residual stresses need relieving, Fe-Ni alloys (Invar-type alloys, with nickel content of 36-49%) exhibit low thermal expansion and have a constant modulus of elasticity over a moderate high temperature range. Nickel has been utilized in the structure of the space shuttles. If aluminum or its alloys are used for structural support on the vehicle, it must not be in the same vicinity as a stainless steel, or stress-corrosion cracking will be induced. Aluminum is anodic to stainless steel (aluminum acting as the anode, steel as the cathode). To electrically insulate aluminum from steel, graphite in grease at the interface is used. Another insulating material for this situation is NiCa, but is porous and will eventually lead to the problem of stress-corrosion cracking. Furthermore, with a porous material, a higher tendency for propagation of dislocations due to voids, is an additional problem. Bolts and screws are to be formed by thread rolling and machining, and can be of aluminum. Gears can be formed by casting, but the resulting porosity of the final product can definitely lead to failure. Forging and powder metal molding are other possibilities. Forging leaves circumferential residual tensile stress and would not be an adequate choice for a forming process since these residual stresses can lead to early fatigue failure. Powder metal molding, in which a fine surface finish can be attained, is the proper choice for forming of the gears. Wire fabric for screens and mesh for tires on the vehicle could be formed from billets subjected to an extrusion process or wire drawing and welded together.

In the past, to reduce thermal stresses and protect the space shuttles during re-entries, light silica tiles have been placed over the skin of the vehicle. The tiles require precision machining, which is very difficult to accomplish with such a brittle material such as this glass. With the tiles, problems were experienced with heat generation on the shuttles due to skin friction. For these reasons, a thin thermal coating may be an alternative to be utilized. Tungsten has been previously used in the absolute environment, but the structure of tungsten makes it inherently brittle, and implies an extremely low tensile strength/density ratio. It is often used at high temperatures due to its high melting point. Ablative materials that (extract heat from the surface by allowing the surface to erode by melting and evaporation at high temperatures) have been used for thermal barrier coatings (to reduce the possibility of hot spots occurring). Added problems exist in the lunar environment: the absence of air and severe radiation effects are present. Many times, surfaces (say, the panels of the mining vehicle, although any surface is susceptible), react with high energy particles (protons, electrons, atoms and molecules). Loss of material through the surface can take place through a process called sputtering (a minimum threshold energy is attained so that particles are able to penetrate the surface). Material is lost when atmospheric density is low. Most mechanical properties are affected due to this loss of material. In instances where abnormal solar conditions are present, "300 angstrom coating of aluminum is lost (one hundred thousandths of a gram per centimeter squared in one month during a period of low-intensity solar wind or in several hours in a solar storm." (p. 436 Rittenhouse and Singletary. Space Materials Handbook. NASA; Washington, D.C.: 1969). Thus the benefit of the choice of titanium alloys is realized, whether the use be for coatings or actual panels and structural support. Further problems arise in the environment due to " . . . surface blistering-the impingement of particles in the environment [onto the vehicle] can increase some materials absorptivity. Microcircuits (formed by evaporation of metallic traces) are especially affected by this. Small blisters can seriously impede optical characteristics of aluminized mirrors due to serious pitting." (p. 436 Rittenhouse and Singletary. Space Materials Handbook. NASA; Washington, D.C.: 1969). As a design parameter, the time for loss of material from initially film covered component, must be equal to or greater than the time for the evaporative loss of a film-free material. Evaportive losses, though, are virtually insignificant in titanium and aluminum alloys. Metallic coatings of cadmium and zinc are possible for fasteners and frames but these evaporative materials could tend to deposit on the optical components. This problem is tackled in the section on visual systems. Ceramics are greatly impeded by the harsh environment; low oxygen pressures or absence of oxygen may increase or induce creep of oxide ceramics by creating vacancies in the lattice and causing the dislocations to move. This will eventually lead to failure. Brasses are volatile components and experience a loss in fatigue strength.

The detrimental effects from radiation are negligible below levels of 1×10^{19} Newtons/cm^2. At higher levels, the materials become embrittled, hardness is increased but the fatigue strength is the property least affected. Aluminum and its alloys tend to change color with induced radiation, affecting its absorptivity and emissivity properties.

Whiskers in material can occur, disabling high impedance circuits. Metallic whiskers can be formed by vapor deposition. Small localized stresses, given adequate time, provide enough energy for the formation of these whiskers. The worst materials for selection with regard to whisker formation are tin, cadmium, and zinc. Bare electrical components need to be coated with epoxy; polyurethane plastic has been used, but plastics tend to "outgas" when placed in a near absolute environment. This is so because of the plastics weakness in ultraviolet rays. Relays, microcircuits, and capacitors should be coated with gold. The charge coupled device used in the visual transmission system of the lunar mining vehicle is surrounded by a tantalum radiation shield.

It has been indicated, on several occasions, that aluminum is weaker than titanium in many properties subjected to the said environment. Titanium exists as a general, all-purpose material suitable for the predescribed situation and exhibits adequate resultant properties after forming.

VIII. CONCLUSIONS AND RECOMMENDATIONS

The scope of this proposal covered the mechanics and preliminary design of machinery for mining on the lunar surface. These general ideas for the collection, movement, and beneficiation of lunar soil in a self-contained vehicle must be followed by more specific studies. These studies should include:

-more efficient use of beneficiation equipment

-more efficient ore recovery of scooper/drivers

-suitable suspension

-support of major components by suitably designed chassis

-reduction of weight through efficient design

-design of ergonomic interface

-more detailed analysis of energy storage capacity

APPENDIX A

AUGER SIZING

Using Conveyors, Inc. catalog # 0177-SC
Model # 16H610

ILMENITE ORE
- Weight — 140-160 lbs/ft^3
- Material code — 150 D_3 37
- Material factor (Fm) — 2.0
- Conveyor loading (%) — 15.0

TOTAL NEEDED CAPACITY — 866 ft^3/hr
SCREW DIAMETER — 16 inches
PITCH DIAMETER — 16 inches
MAXIMUM LUMP SIZE — 3 inches
CONVEYOR SPEED — — —

$$S_c = \frac{C_v}{C_{v_1}},$$

C_v = total needed capacity
C_{v_1} = conveyor capacity @ 1 rpm = 22.7 ft^3/hr

$$S_c = \frac{866 \text{ ft}^3/\text{hr}}{22.7 \text{ ft}^3/\text{hr}}$$

$$= 38.15 \text{ rpm}$$

POWER REQUIREMENTS — —

$$HP_f = \frac{L_c S_c F_c F_b}{1000000},$$

L_c = length of conveyor = 20 ft
F_c = conveyor dia factor = 107
F_b = hanger bearing factor = 1.7

$$HP_f = \frac{(20)(38.15)(107)(1.7)}{1000000}$$

$$= 0.139, \text{ conveyor friction HP}$$

$$HP_m = \frac{C_v M L_c F_m}{1000000}$$

M = average material weight = 150 lbs/ft^3

$$HP_m = \frac{(866)(150)(20)(2.0)}{1000000}$$

$$= 5.2, \text{ conveyed material HP}$$

$$HP_t = \frac{(HP_f + HP_m)\,F_o}{\text{drive eff.}},$$

F_o = conveyor overload factor = 1.0

$$HP_t = \frac{(0.139 + 5.20)(1.0)}{0.85}$$

$$= 6.28, \text{ conveyor total HP}$$

OUTSIDE DIAMETER OF PIPE — 4 inches
INSIDE DIAMETER OF PIPE — 3 1/2 inches
THICKNESS OF FLIGHT (HELICOID)
- INNER EDGE — 5/16 inch
- OUTER EDGE — 5/32 inch

COMPLETE SCREW WEIGHT — 19 lbs/ft

APPENDIX B

TRUCK CAPACITY CALCULATIONS

$$(183 \text{ lit days/year})(24 \text{ hrs/day}) = 4392 \ \frac{\text{WORKING HRS}}{\text{YEAR}}$$

$$\frac{3.76 \times 10^6 \text{ metric tons/year}}{4392 \text{ hrs/year}} = 856 \ \frac{\text{TONS}}{\text{HR}} \quad \text{TO BE DUG}$$

ASSUMING THE USE OF FOUR MINING VEHICLES ---

Each truck must collect ---

$$\frac{856 \text{ metric tons/hr}}{4 \text{ vehicles}} = \frac{214 \text{ metric tons/hr}}{\text{vehicle}}$$

$$214 \ \frac{\text{metric tons/hr}}{\text{truck}} \left(\frac{m^3}{1.75 \text{ metric tons}}\right)$$

$$= 122.3 \ \frac{m^3/hr}{\text{truck}}$$

TO FIND THE VELOCITY OF THE TRUCK ---

$$\frac{\text{Volume collected}}{\text{hour}} = \left(\frac{\text{Volume collected}}{\text{meter}}\right)\left(\frac{\text{meters}}{\text{hour}}\right)$$

$$122.3 \ m^3/hr = (.72 \ m^3/m)(\text{VELOCITY})$$

$$\text{VELOCITY} = 170 \ m/hr$$

EACH TRUCK WILL RETAIN 20% OF BENEFICATION ---

$$\left(214 \ \frac{\text{metric tons}}{hr}\right)(0.20) = 42.8 \ \frac{\text{metric tons}}{hr}\left(\frac{m^3}{1.75 \text{ metric tons}}\right)$$

$$= 24.5 \ m^3/hr$$

ASSUMING 4 UNLOADINGS PER HOUR, EACH LOAD WOULD BE 6.125 m^3/hr. RETAINING BINS WOULD BE $(2.2 \times 2.6 \times 1.1)\ m^3$.

APPENDIX C

POWER DESIGN EQUATIONS

NOMENCLATURE:

h_b = OUTSIDE NON-RIM THICKNESS

h_c = CENTER THICKNESS

h_o = RIM THICKNESS

r_b = RADIUS WITHOUT RIM

r_o = RADIUS WITH RIM

K = SHAPE FACTOR

m = MASS

I = MOMENT OF INERTIA

ρ = MATERIAL DENSITY

ω = ANGULAR VELOCITY

σ_b = MAXIMUM STRESS

ν = POISSON'S RATIO

r = ARBITRARY RADIUS

h = ARBIRARY THICKNESS

$\chi = r/r_o$

DESIGN EQUATIONS:

A) $\alpha = \dfrac{h_b}{h_c}$ SET EQUAL TO 1 TO AVOID STRESS CONCENTRATIONS

B) $B = \dfrac{\rho \omega^2 r_o^2}{2 \sigma_b}$

C) $\beta = \dfrac{r_b}{r_o} = \left[\dfrac{1}{B\alpha} \left[\alpha - 1 + 2\sqrt{\dfrac{\alpha^2 B (B - 1 + \nu)}{(1+\nu)^2} - \dfrac{(\alpha - 1)^2}{4}} \right] - \dfrac{1+\nu}{1-\nu} \right]^{1/2}$

D) $h_o = \alpha h_c e^{-B\beta^2}$

E) $K = \dfrac{1 + [B^2(1-\beta)^4/2 - B\beta^2 - 1] e^{-B\beta^2}}{1 + [B(1-\beta^2) - 1] e^{-B\beta^2}}$

F) $m = \pi \rho h_c r_o^2 \dfrac{\{[\alpha B (1-\beta^2) - 1] e^{-B\beta^2} + 1\}}{B}$

G) $I = \pi \rho h_c r_o^4 \dfrac{\{[\alpha B^2 (1-\beta^4)/2 - B\beta^2 - 1] e^{-B\beta^2} + 1\}}{B^2}$

H) $\dfrac{h}{h_c} = e^{-B\chi^2}$ GIVES SHAPE PROFILE

APPENDIX C (CONT'D.)

SINCE A HIGH K VALUE IS DESIRED, CHOOSE $B = 3$.

FROM C), $\beta = 0.803$

FROM E), $K = 0.947$

CHOOSE $r_o = 1.5\ m$ TO FIT WITHIN VEHICLE

SINCE $\rho = 1400\ kg/m^3$ AND $m = 970\ kg$, THEN FROM F),

$h_c = 0.327\ m$

$\sigma_t = 2077\ MPa$ SO FROM B), $\omega = 1989\ RAD/s = 19{,}000\ RPM$

FROM H), $h = 0.327 \cancel{m} \left[1 - 3\left(\frac{r}{1.5m}\right)^2\right] m$.

APPENDIX D - BENEFICIATION EFFICIENCY ANALYSIS

- based on model in ref. [1]

coarse and fine separation combined:
- -20 mesh screen used to filter out all particles greater than 1mm
- -200 mesh screen used to filter smaller particles

M - mass of ore mined - 78905 lb_f/hr
m_i - mass of ilmenite concentrate
e - mass efficiency of separation - 0.93
f - fractions in original ore
T - mass of tailings

subscripts and superscripts:

c - electrostatic   f - fine
m - magnetic   s - start
c - coarse

$$m_i = \left[f_s e_s (f_e^f + f_e^c) e_c^{f+c} \; f_m^{f+c} \; e_m^{f+c} \; f_e^{f\ell+c\ell} \; e_e^{f\ell+c\ell} \right] M$$

$$= [(0.99)(0.93)(0.78)(0.93)(0.5)(0.93)(0.13)(0.93)] \, 78905 \; lb_f/hr$$

$$= 2960 \; lb_f/hr$$

- due to expected lower efficiencies in the electrostatic and magnetic separation processes (due to limited size and power) only 20% total efficiency is expected and further separation may have to be carried out at the lunar base:

$$m_i = 0.20 (78905 \; lb_f/hr)$$

$$= 15781 \; lb_f/hr$$

$$m_i = \frac{6(15781\ lb_m)}{hr} \bigg/ \frac{1\ Kg}{2.2046\ lb_m} = 42905\ Kg/hr$$

electrostatic separator #1 -

begin with : 78905 lb_f/hr = 122.3 m^3/hr

produce : 0.8(78905) = 63124 lb_f/hr = 97.8 m^3/hr

magnetic separator:

begin with : 63124 lb_f/hr

end with : 0.5(63124) = 31562 lb_f/hr = 48.9 m^3/hr

electrostatic separator #2 -

begin with : 31562 lb_f/hr

end with : 0.5(31562) = 15781 lb_f/hr = 24.5 m^3/hr

Power requirements:

electrostatic separator #1 -

25000V, 300 HZ

$V = 25000 \sin \omega t$ $\qquad \omega = 300(2\pi) = 1885$ rad/s

$$\frac{dV}{dt} = 1885(25000) \cos 1885t$$

$$P = CV\frac{dV}{dt} \qquad C = \varepsilon_0 \frac{A}{d}$$

$$= 9.35 \times 10^{-10}\ (1885)(25000)^2 \qquad = \frac{8.85 \times 10^{-12}(4.4m)(1.22m)}{0.0508m}$$

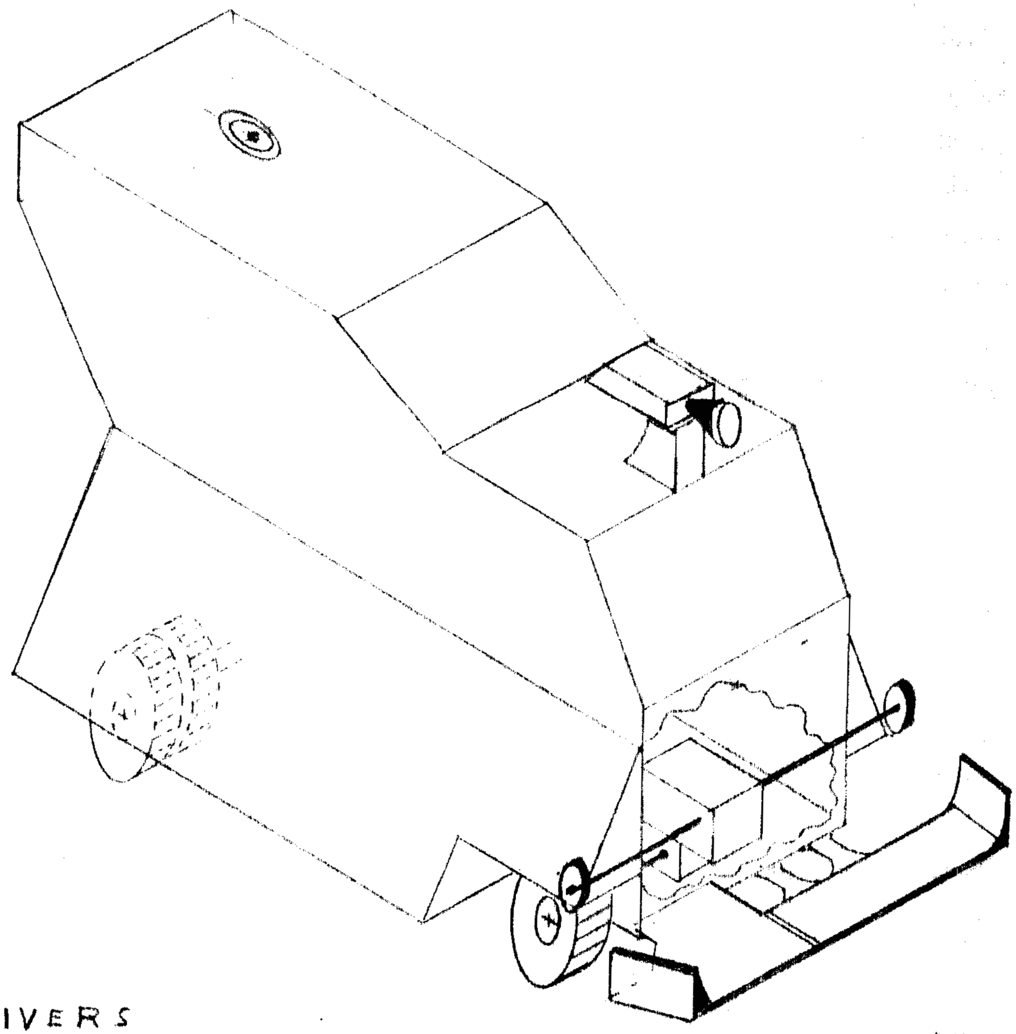
$$= 1.1\ KW \qquad = 9.35 \times 10^{-10}\ F$$

conveyors - each . . . . 2.24 KW

magnetic separator . . . . 6.70 KW

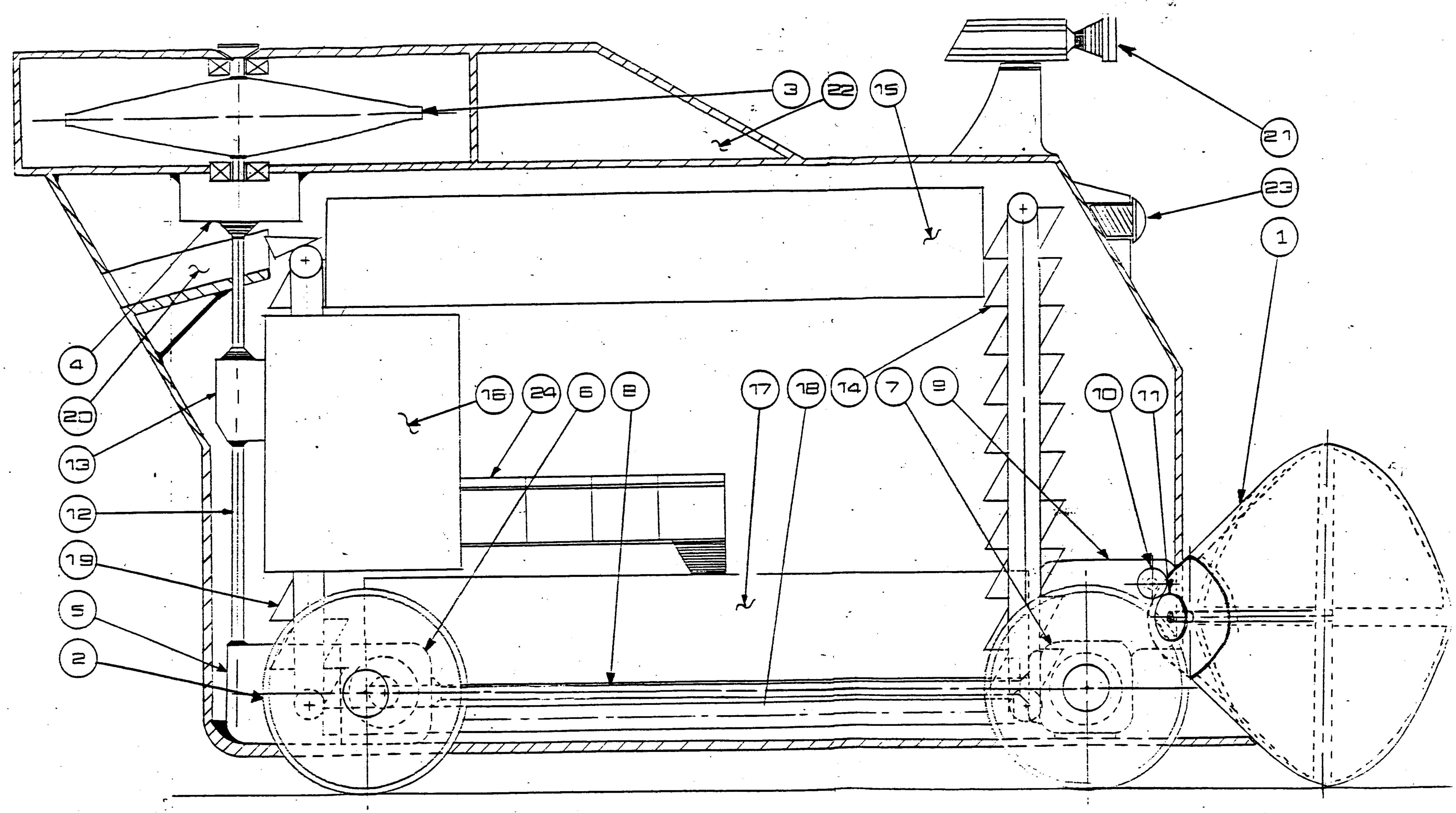
Total power . . . . 13.38 KW

APPENDIX E. LIST OF FIGURES



NOTE:
SCOOPER / DRIVERS
OMITTED FOR
CLARITY

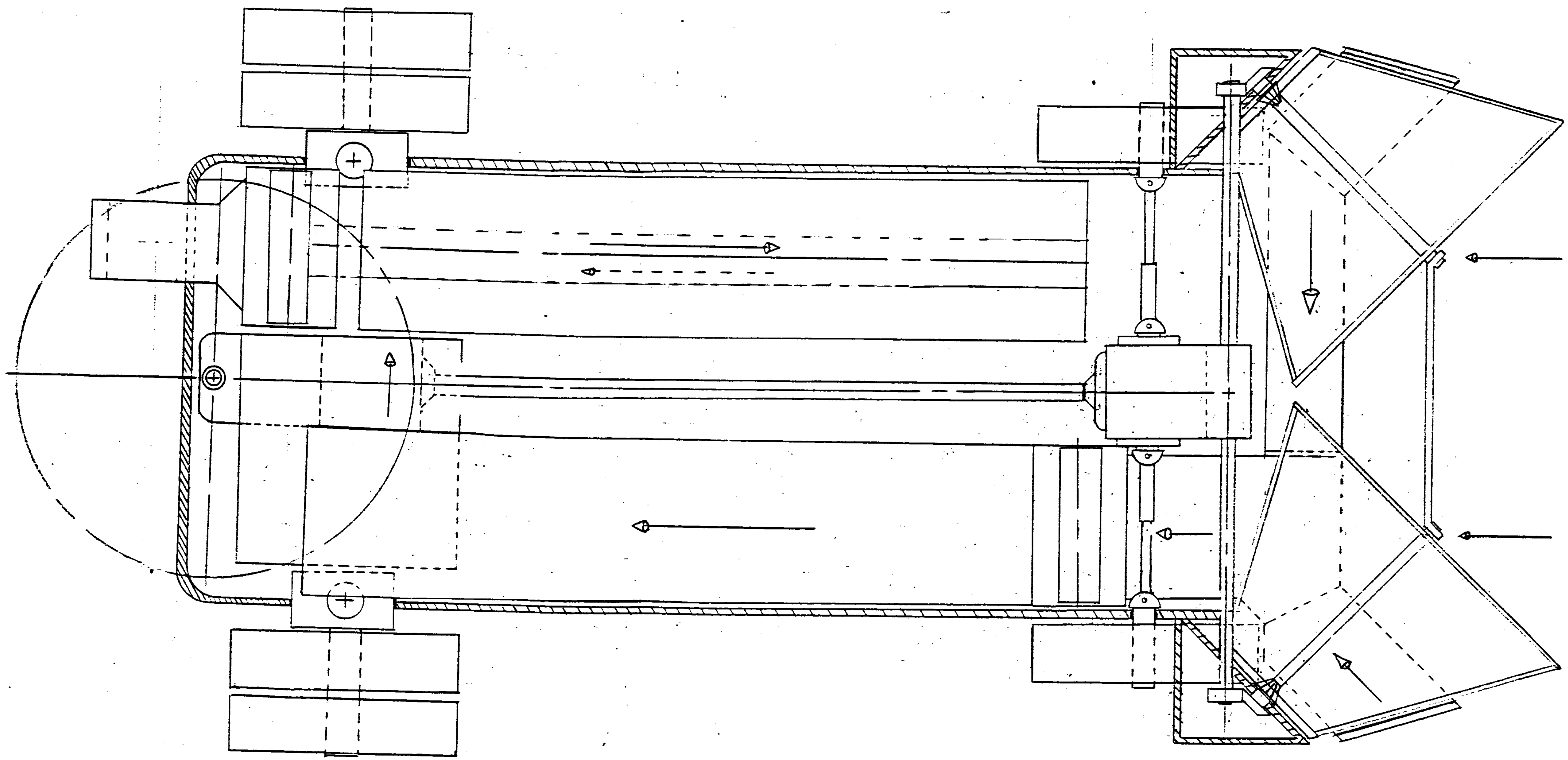
OVERALL ISOMETRIC VIEW
LUNAR MINING VEHICLE
GROUP 5 3/11/86
FIGURE # 1



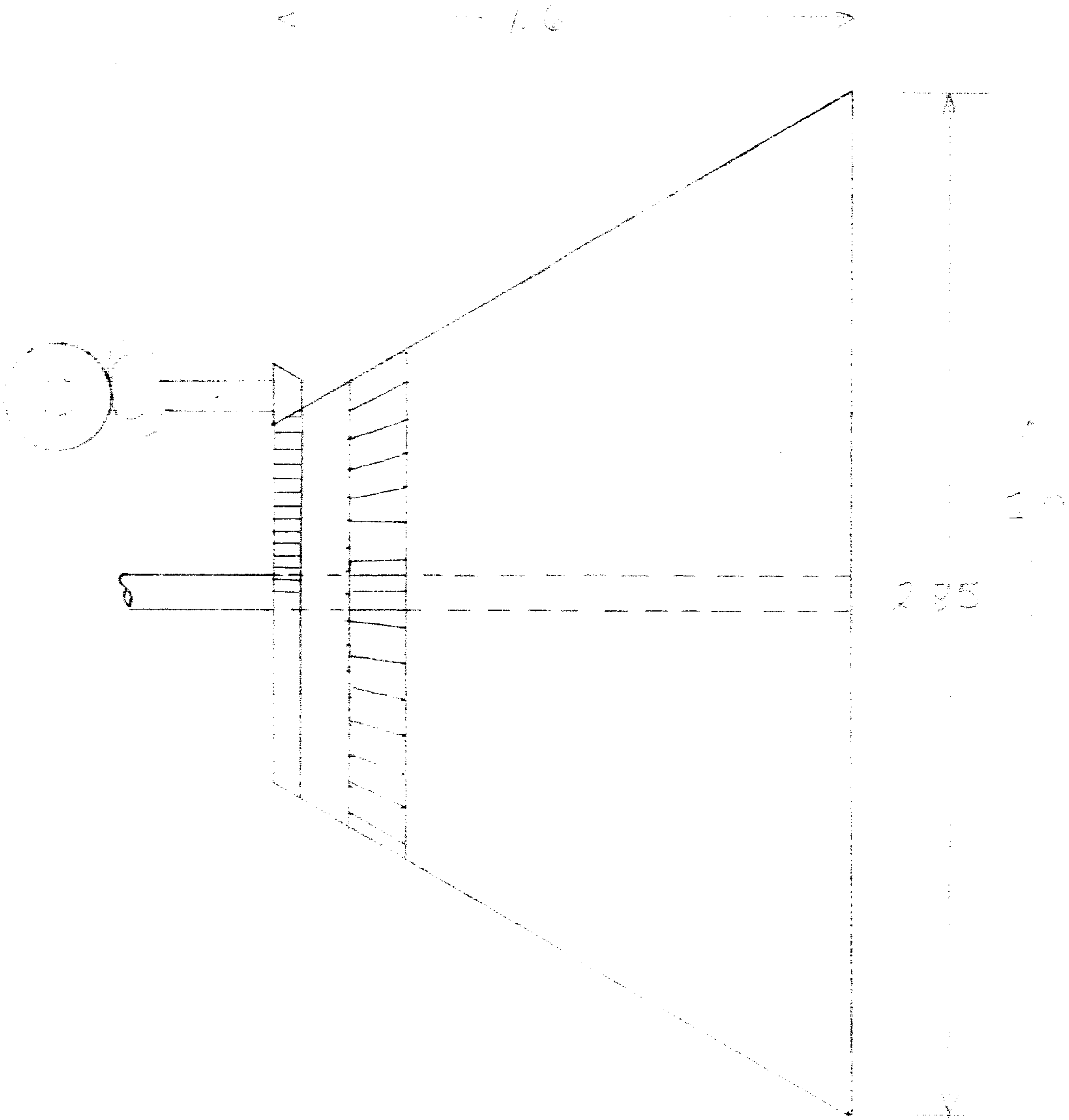
MAIN ELEVATION VIEW
LUNAR MINING VEHICLE
GROUP 5
MARCH 11, 1986
FIGURE 2
DRAWN BY:

LUNAR MINING VEHICLE PARTS LIST
FOR FIGURE 2

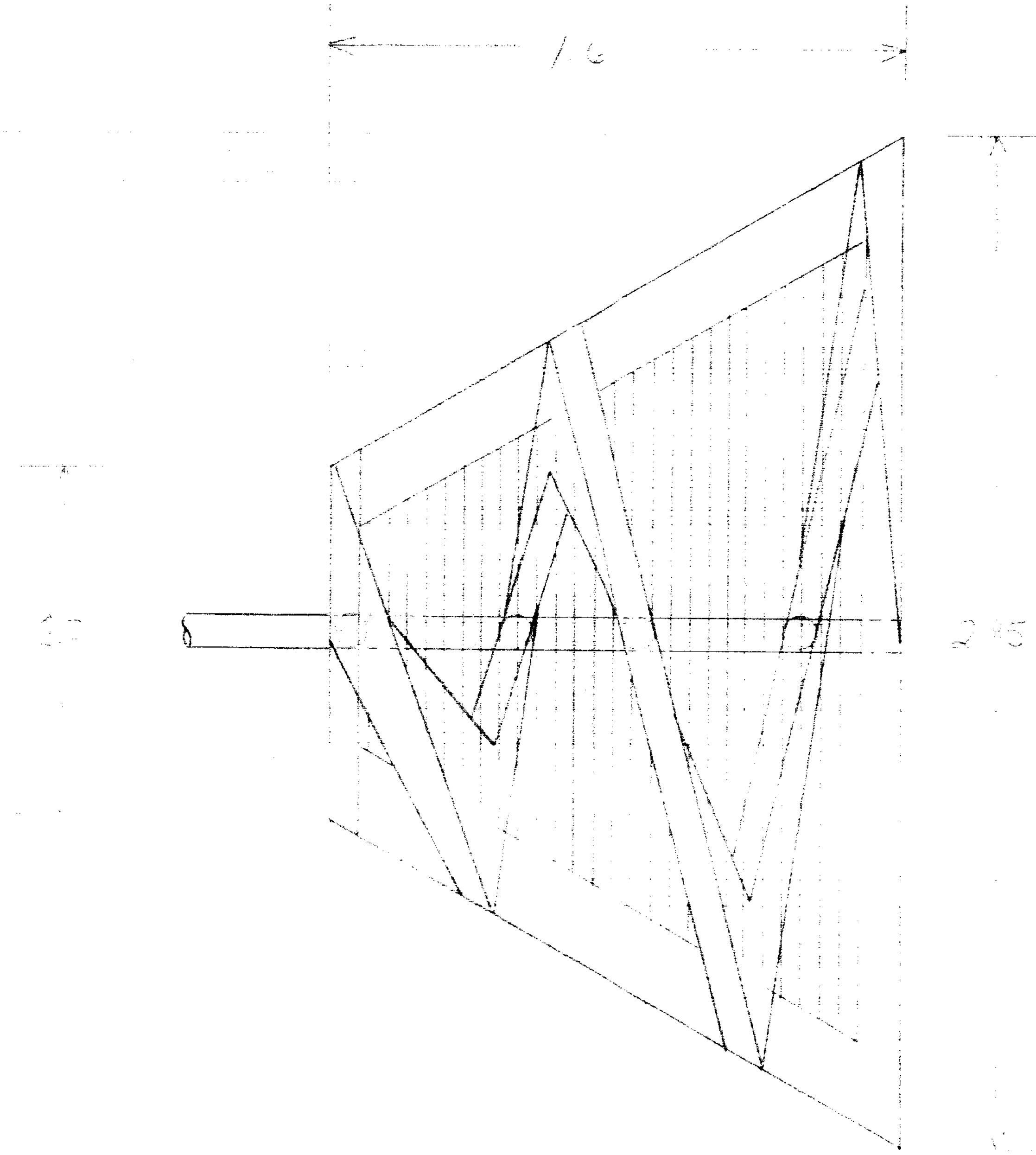
ITEM NUMBER	DESCRIPTION	REFERENCE FIGURE #
1	SCOOPER / DRIVER	4,5,6
2	ALUMINUM OPEN MESH WHEELS	
3	FLYWHEEL	7
4	SPEED REDUCER	
5	RIGHT ANGLE DRIVE / CONTINUOUSLY VARIABLE TRANSMISSION	
6	REAR DIFFERENTIAL	
7	FRONT DIFFERENTIAL	12
8	DRIVE SHAFT	
9	SCOOPER/DRIVER DIFFERENTIAL	
10	SCOOPER/DRIVER DRIVE SHAFT	
11	SCOOPER/DRIVER GEAR	
12	FLYWHEEL SHAFT	
13	GENERATOR	
14	FIRST BUCKET ELEVATOR	8
15	FIRST ELECTRO-STATIC SEPARATOR	
16	MAGNETIC SEPARATOR	
17	SECOND ELECTRO-STATIC SEPARATOR	11
18	SCREW CONVEYOR	9
19	SECOND BUCKET ELEVATOR	9
20	EXIT CHUTE	
21	[illegible]	4
22	ON-BOARD COMPUTER / ELECTRONIC CONTROLS	13
23	LIGHTING	
24	STORAGE BATTERIES - NICAD	



MAIN PLAN VIEW
LUNAR MINING VEHICLE
GROUP 5
MARCH 11, 1986
FIGURE 3
DRAWN BY:



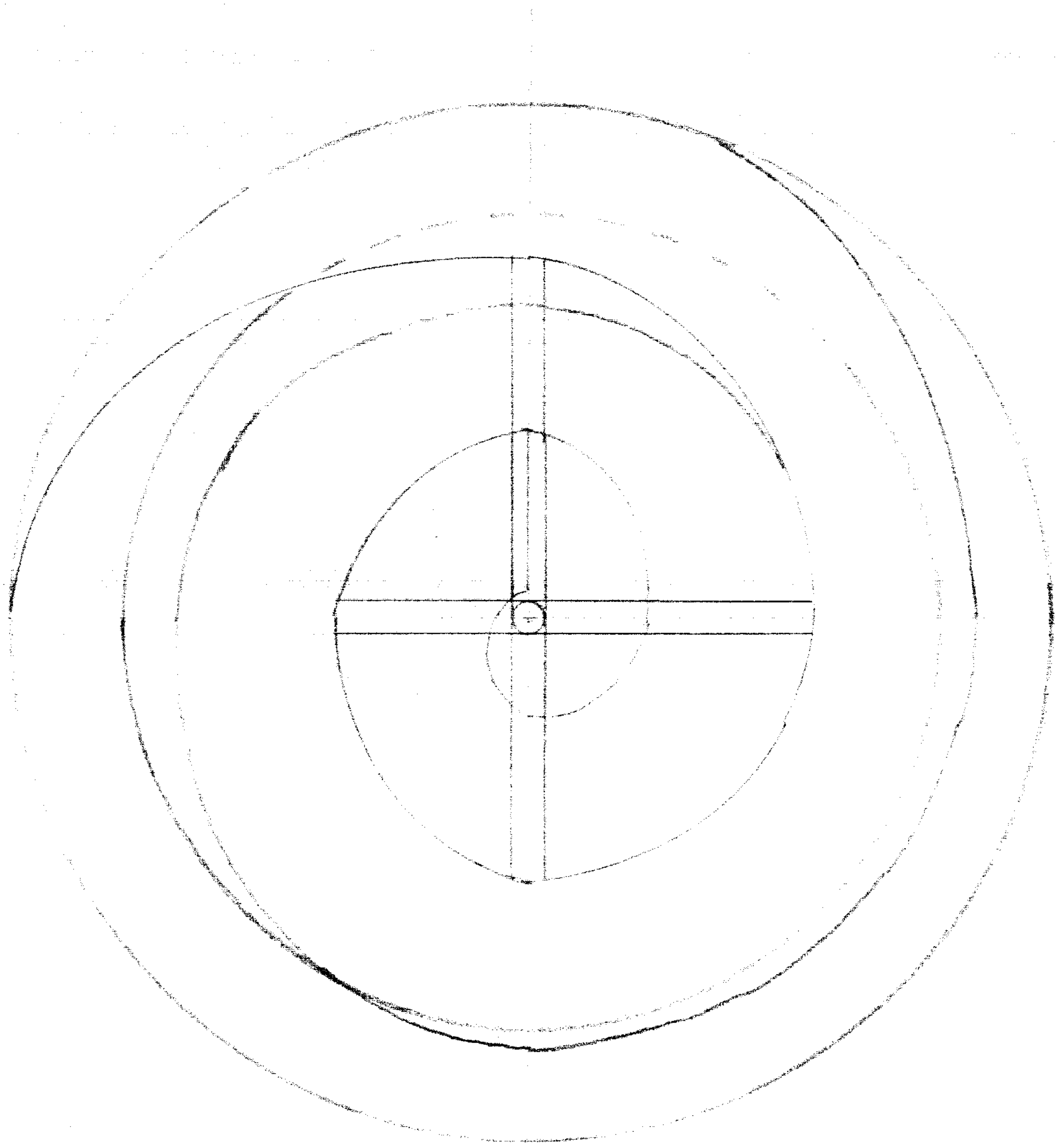
DETAIL OF SCOOPER/DRIVER
LUNAR MINING VEHICLE
GROUP 5
MARCH 11, 1986
FIGURE #4



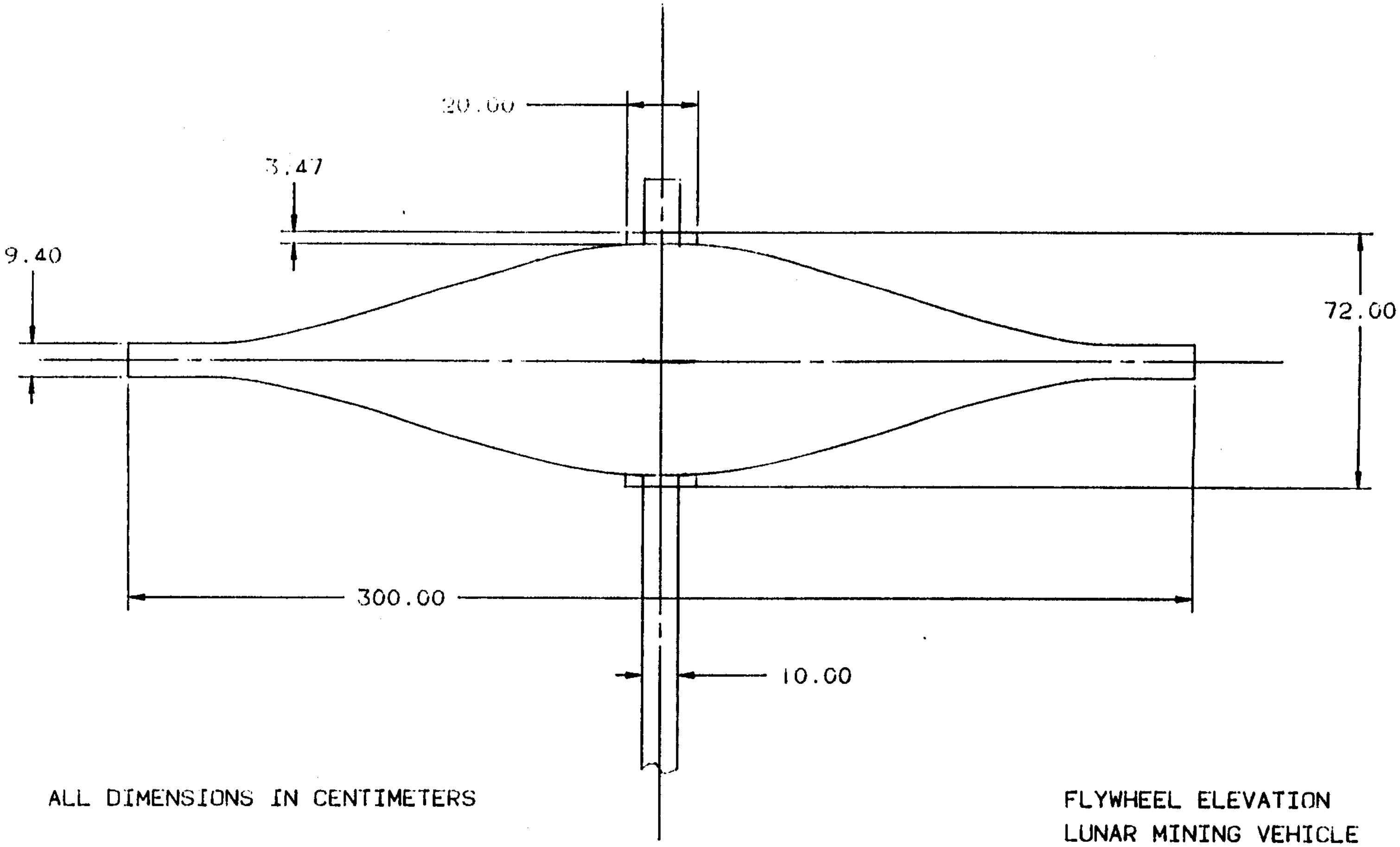
DIMENSIONS IN METRES

CROSS SECTION OF
SCOOPER/DRIVER
LUNAR MINING VEHICLE
GROUP 5

FIGURE #5



END VIEW OF
SCOOPER/DRIVER
LUNAR MINING VEHICLE
GROUP 5 3/11/86
FIGURE 6

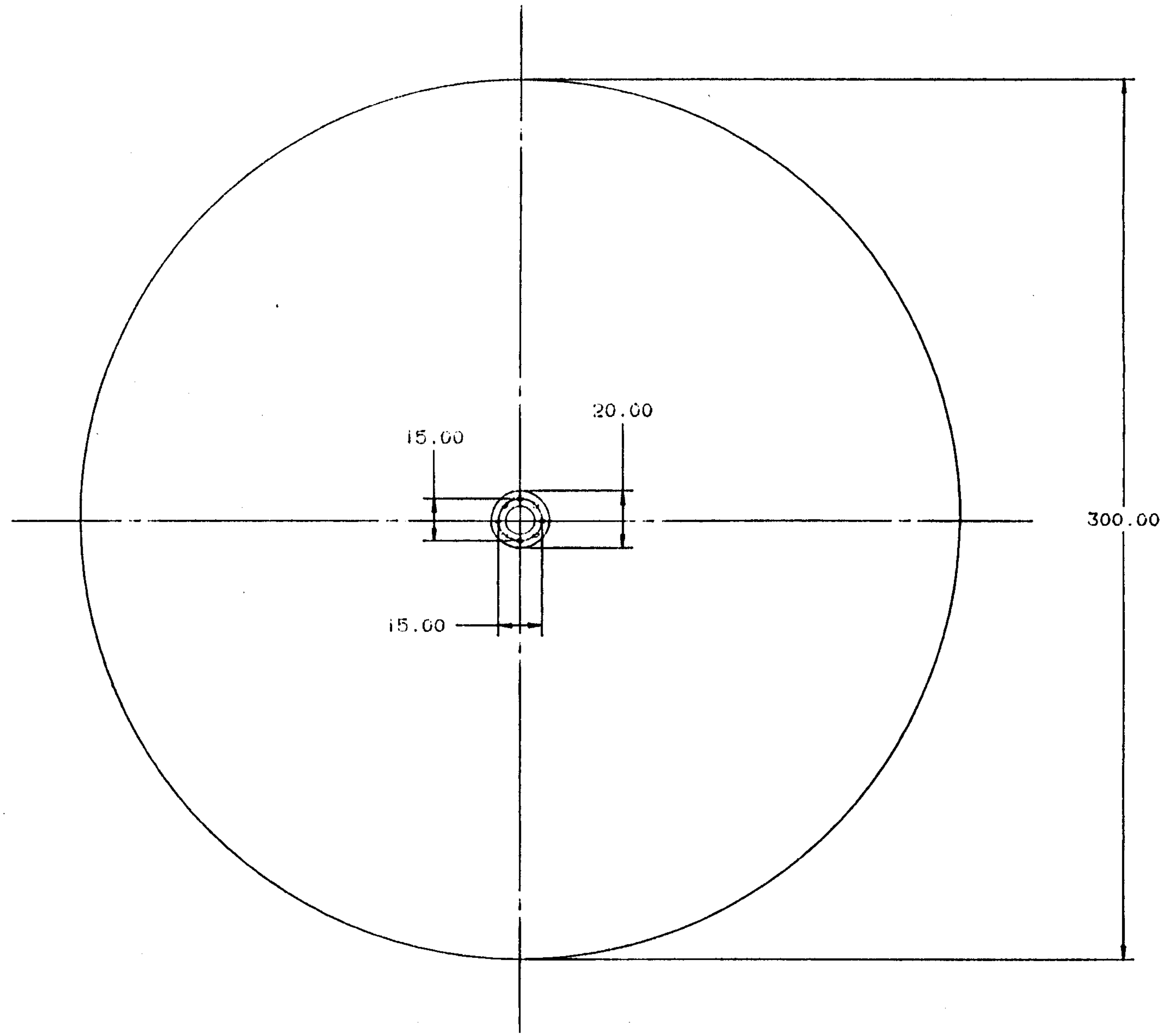


ALL DIMENSIONS IN CENTIMETERS

FLYWHEEL ELEVATION
LUNAR MINING VEHICLE
GROUP 5
MARCH 11, 1986

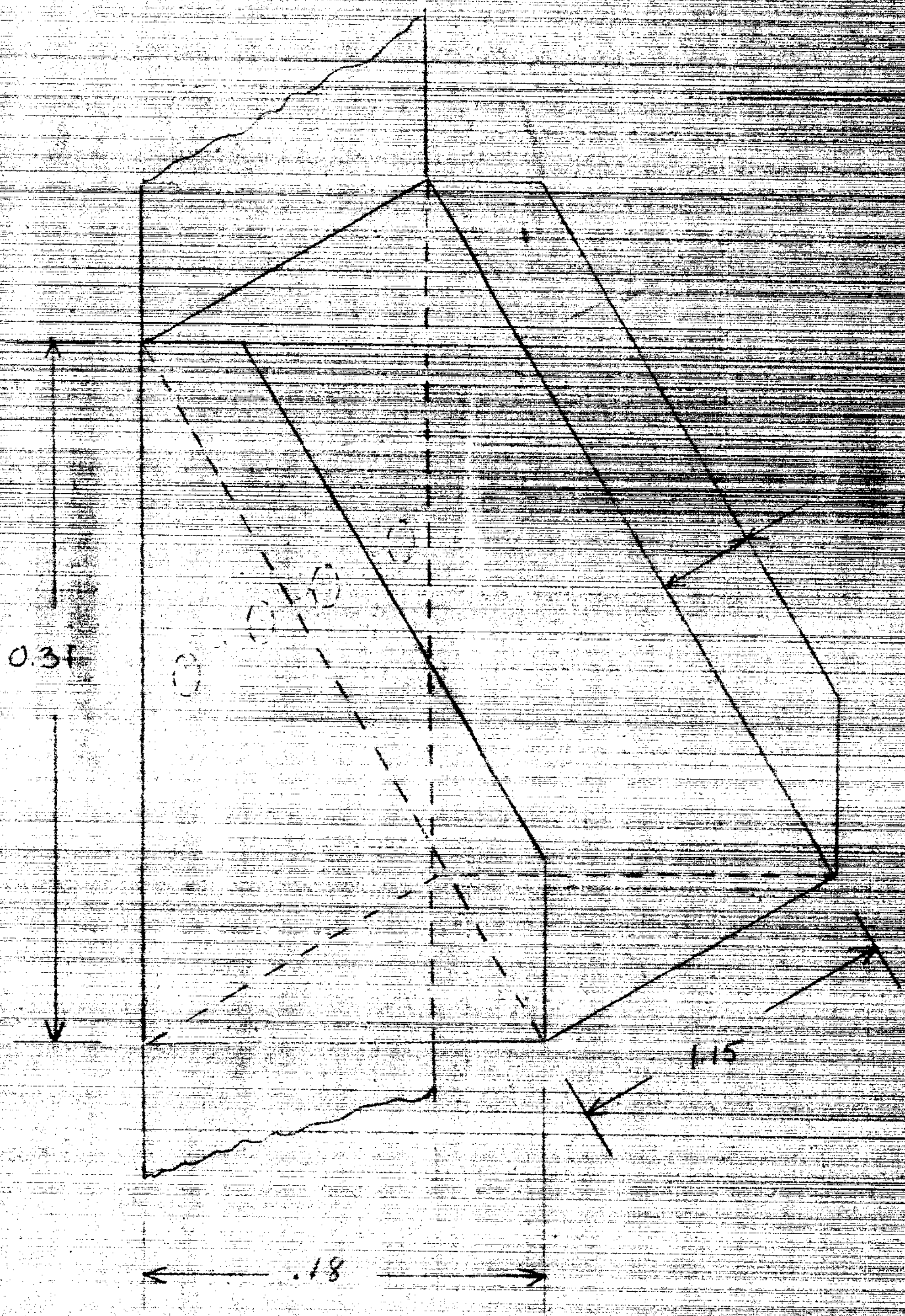
FIGURE 7A

DRAWN BY: R D H



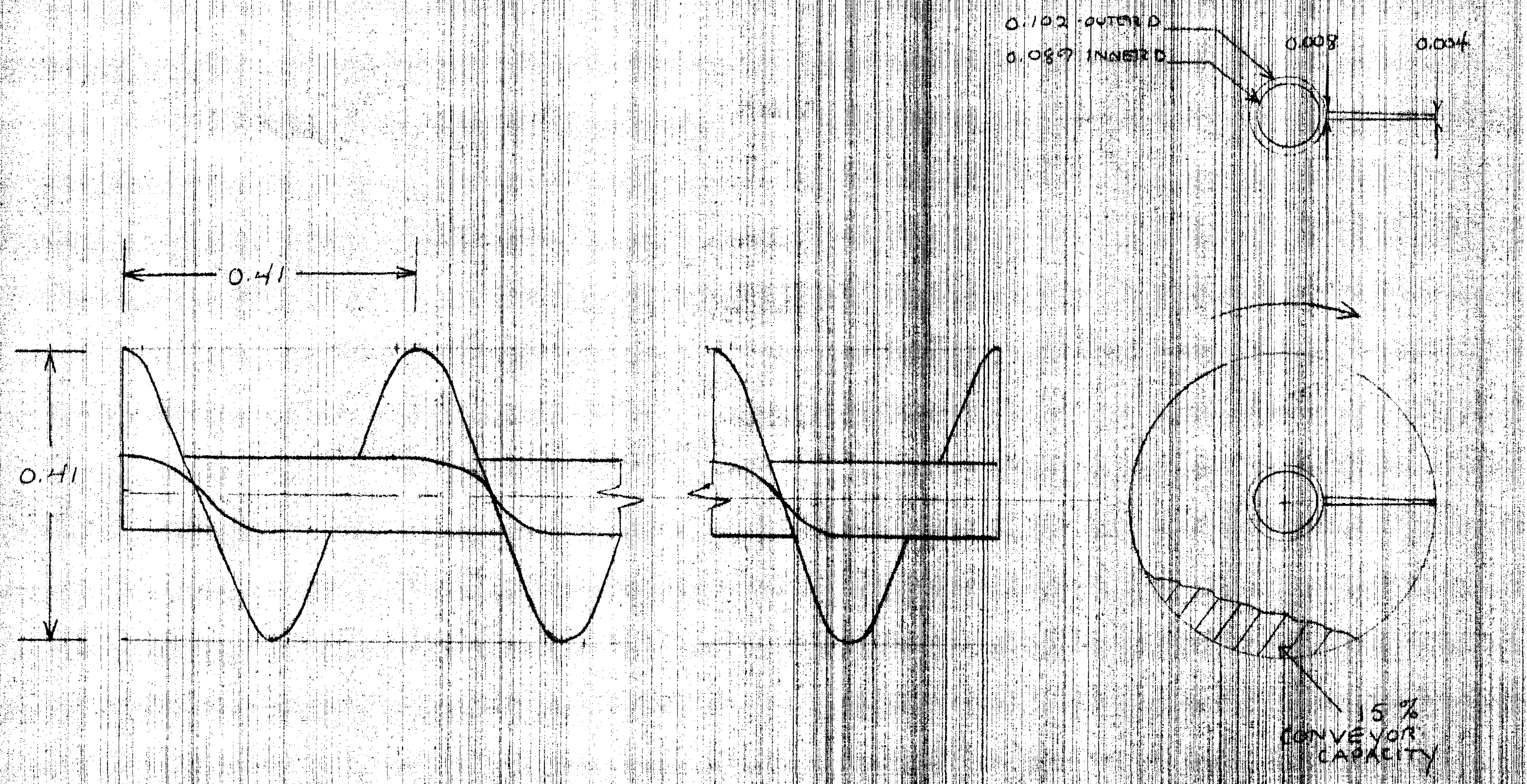
ALL DIMENSIONS IN CENTIMETERS

FLYWHEEL PLAN VIEW
LUNAR MINING VEHICLE
GROUP 5
MARCH 11, 1986
FIGURE 7B
DRAWN BY: R D H



DIMENSIONS IN METERS

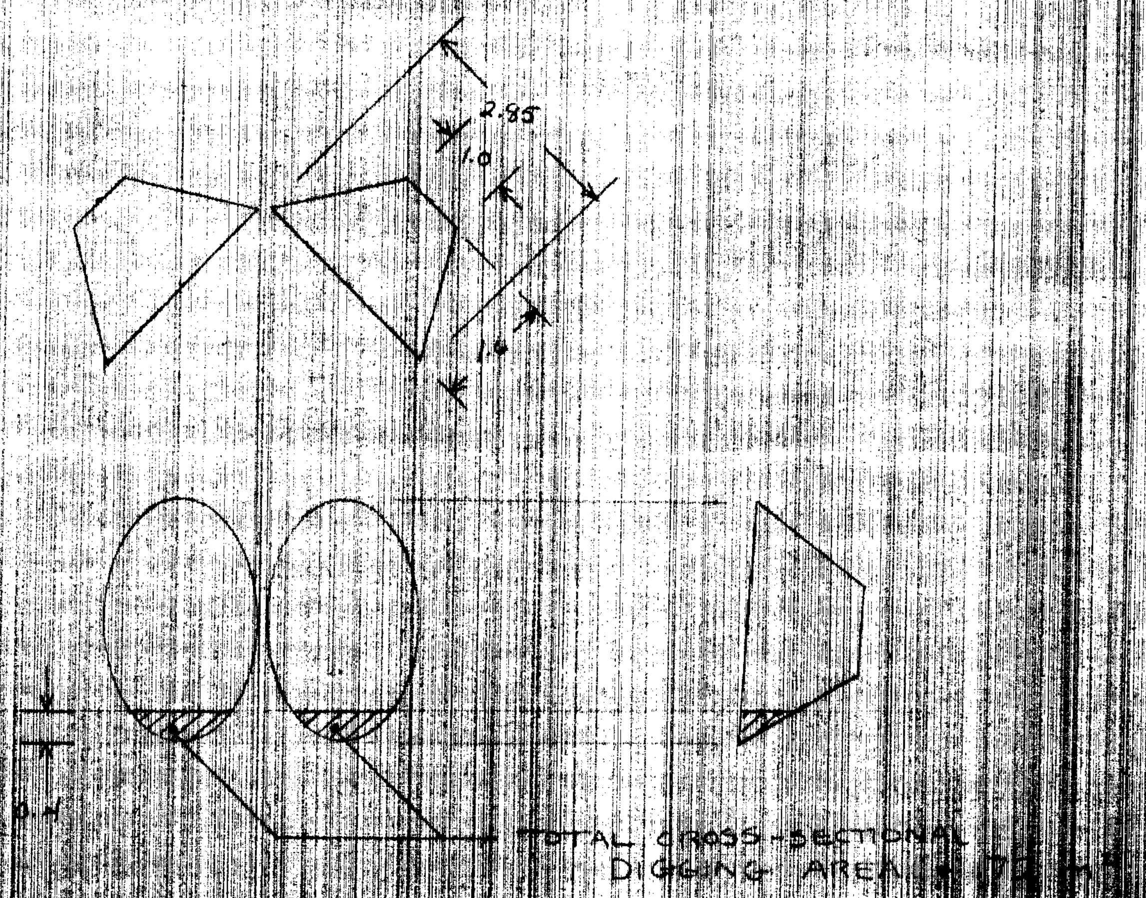
DETAIL OF BUCKET ELEVATOR
LUNAR MINING VEHICLE
GROUP 5
MARCH 11, 1986
FIGURE # 8

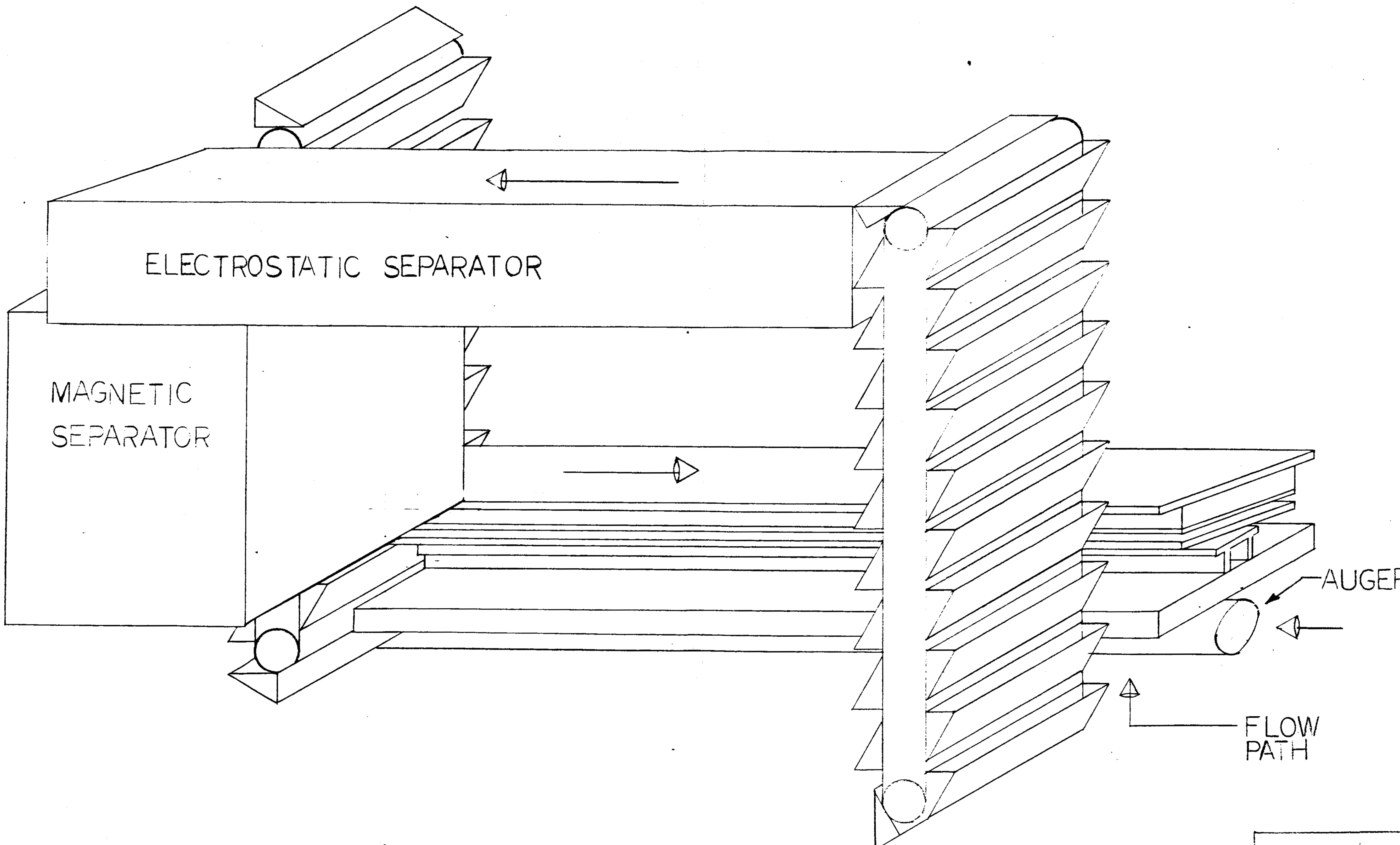


AUGER CONVEYOR

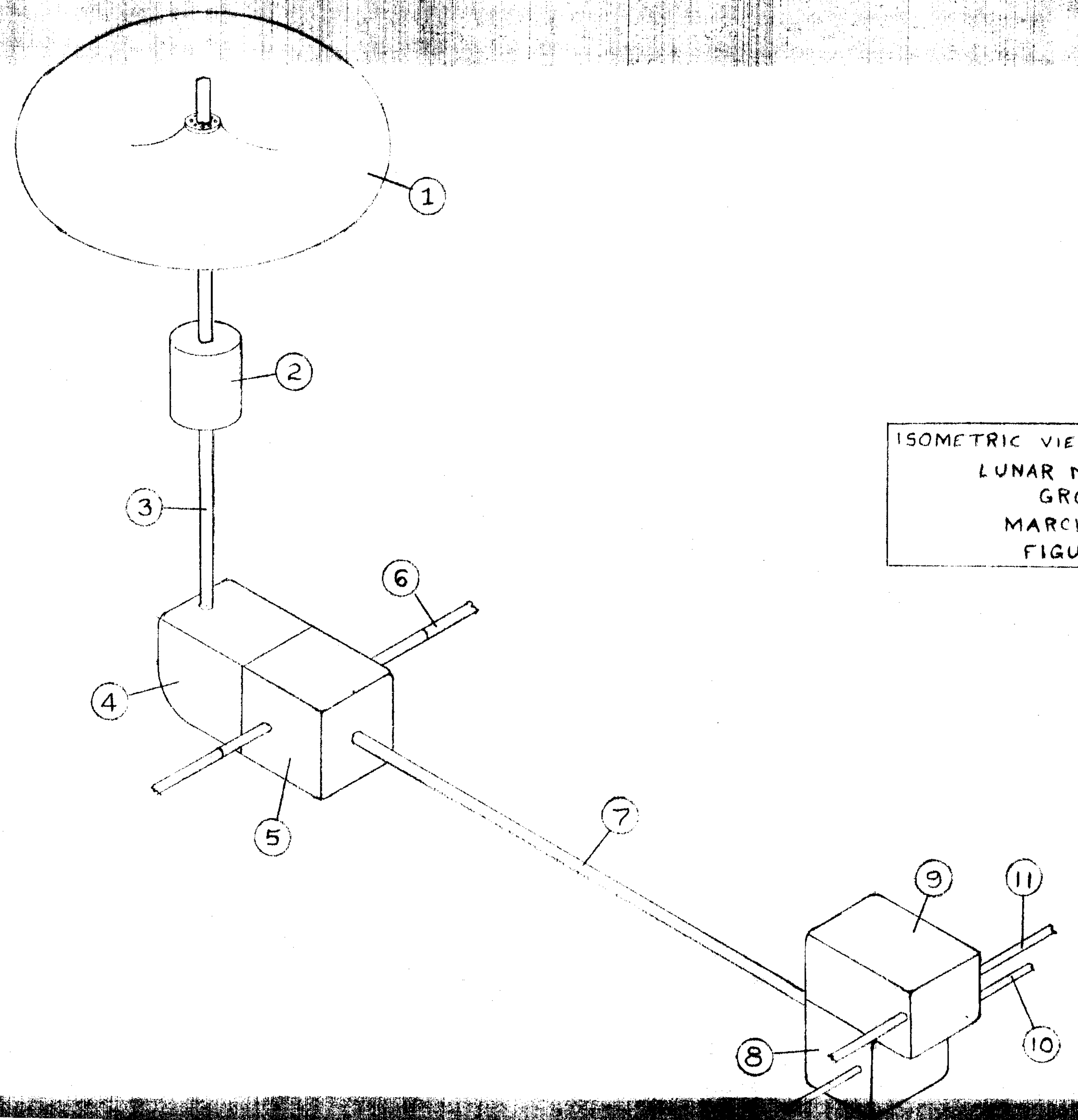
LUNAR MISSION VEHICLE

GROUP 5


2.85
1.0
1.4
0.4
TOTAL CROSS-SECTIONAL
DIGGING AREA



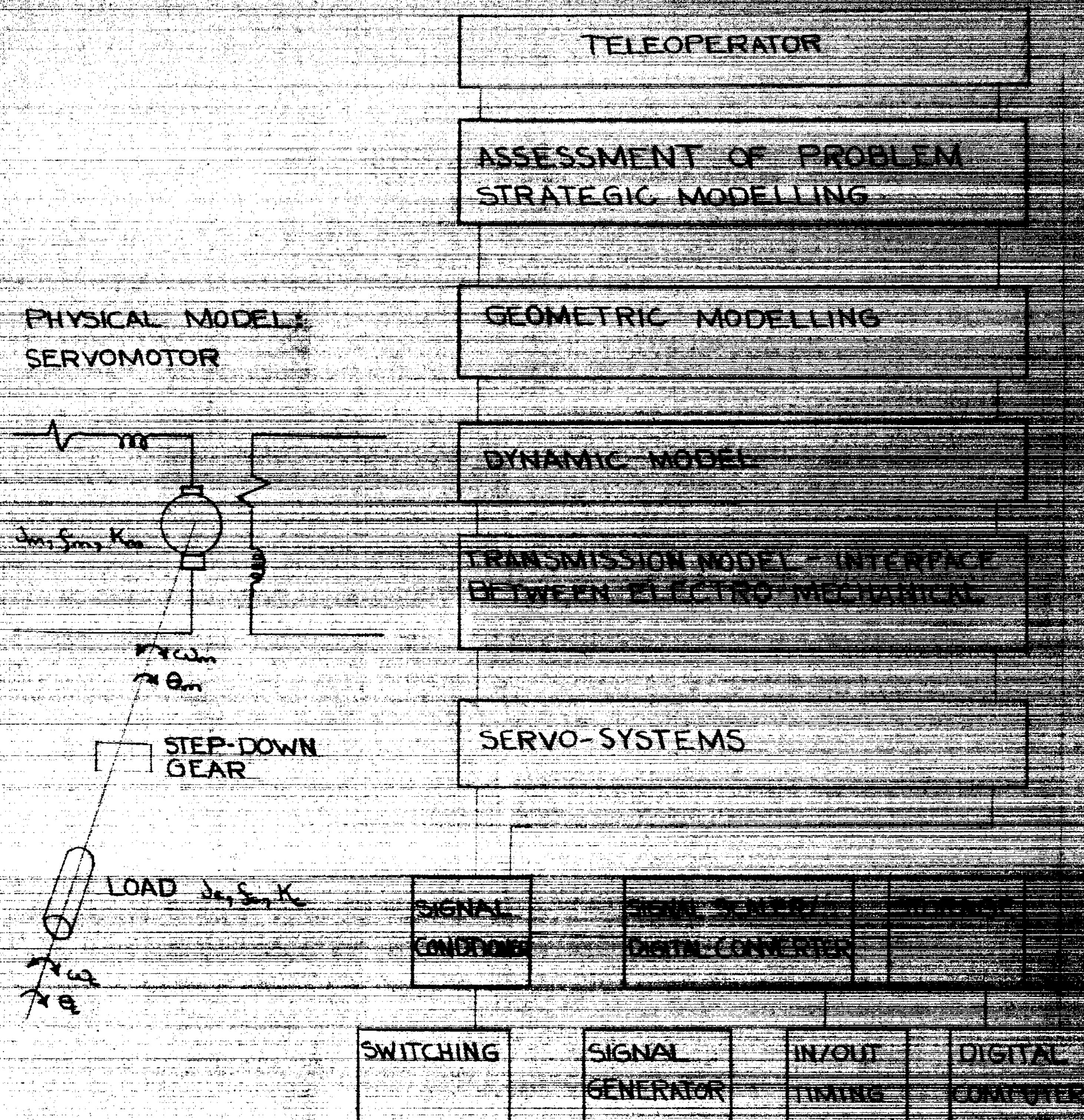
ISOMETRIC VIEW OF
BENIFICATION
LUNAR MINING VEHICLE
GROUP 5 3/11/86
FIGURE # 11



ISOMETRIC VIEW OF DRIVE TRAIN
LUNAR MINING VEHICLE
GROUP 5
MARCH 11, 1986
FIGURE 12

DRIVE TRAIN PARTS LIST
FOR FIGURE 12

ITEM NUMBER	DESCRIPTION
1	FLYWHEEL
2	GENERATOR
3	FLYWHEEL SHAFT
4	RIGHT ANGLE DRIVE / CONTINUOUSLY VARIABLE TRANSMISSION
5	REAR DIFFERENTIAL
6	REAR WHEEL SHAFT
7	DRIVE SHAFT
8	FRONT DIFFERENTIAL
9	SCOOPER/DRIVER DIFFERENTIAL
10	FRONT WHEEL SHAFT
11	SCOOPER/DRIVER SHAFT



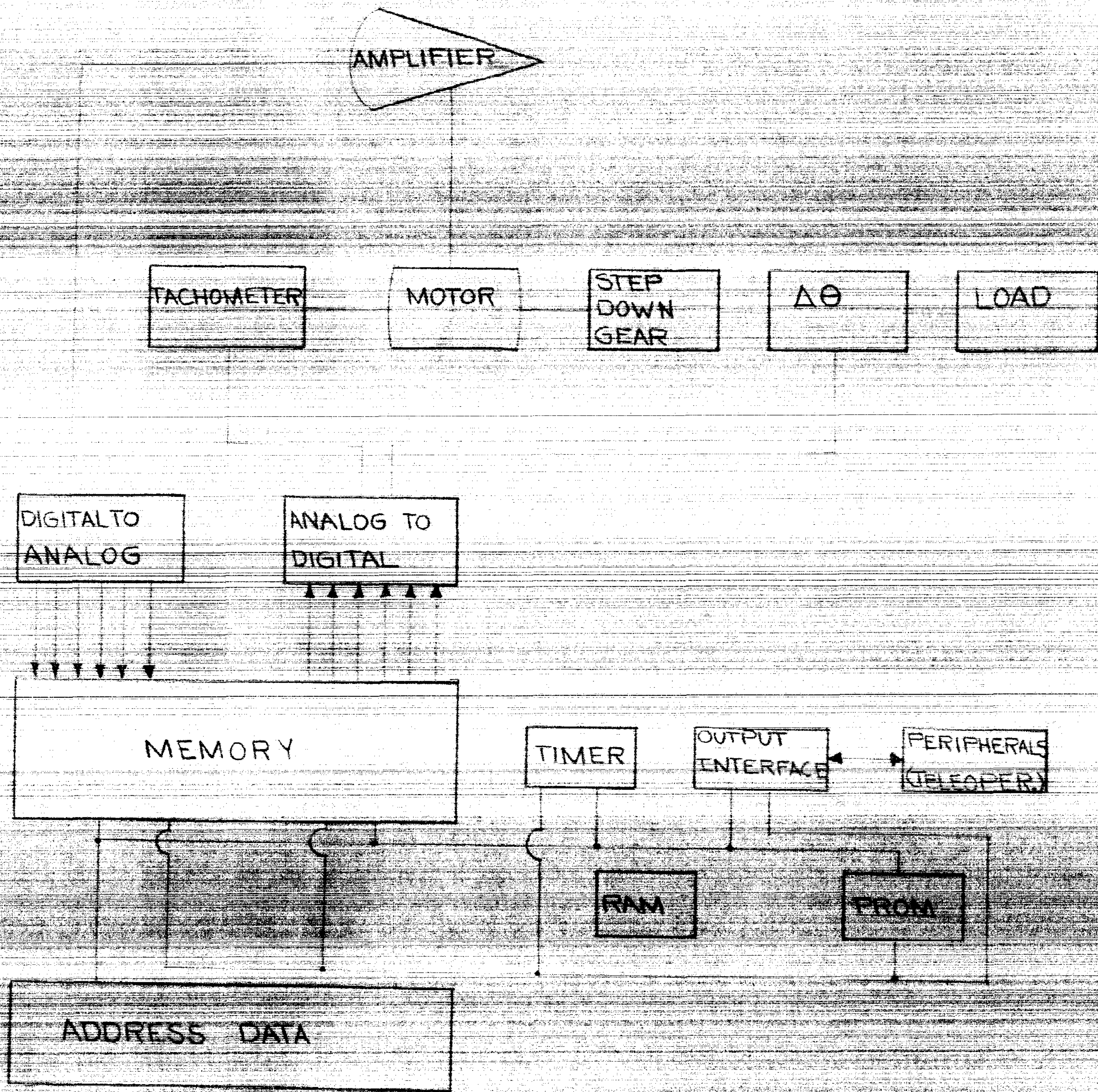
VISUAL / CONTROLS

FLOW CHARTS

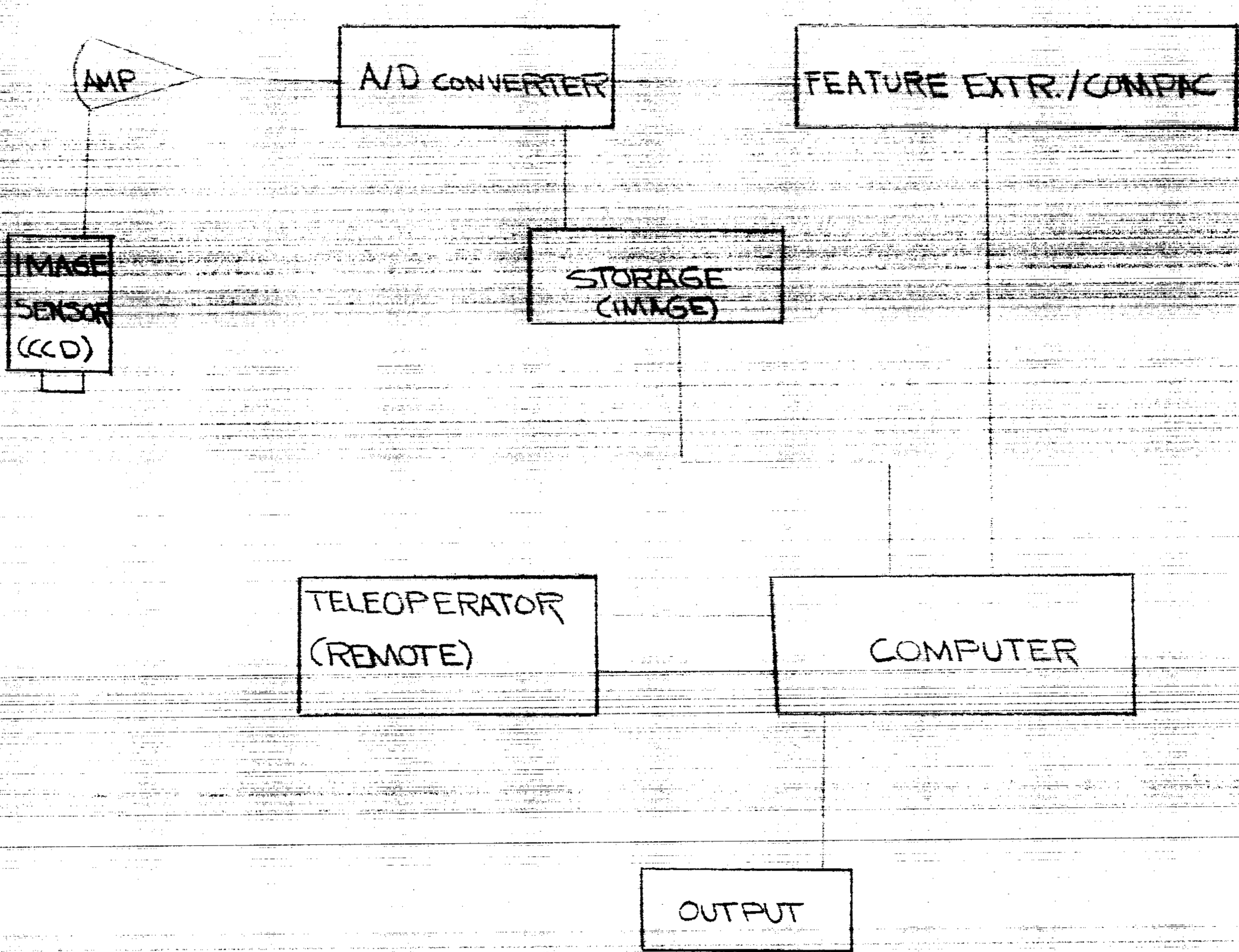
LUNAR MINING PROJECT

GROUP 5 MARCH 11, 1986

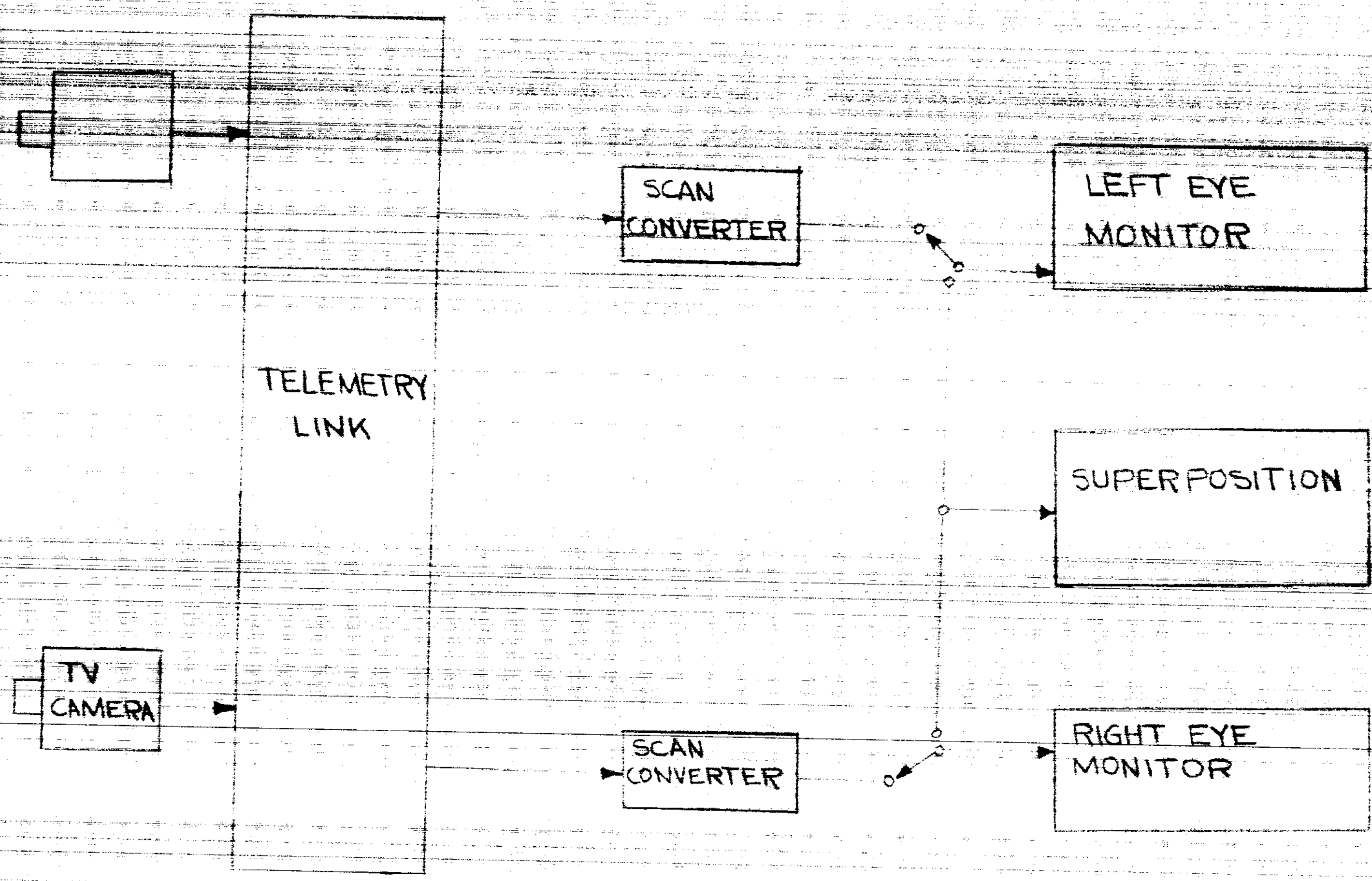
FIG. 13a DRAWN BY: LA



VISUAL / CONTROLS
FLOW CHARTS
LUNAR MINING PROJECT
GROUP 5 MARCH 11, 1986
FIG. 13(a) DRAWN BY: LA

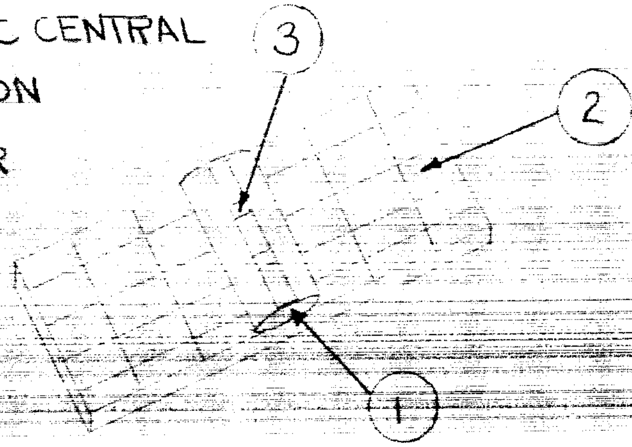


VISUAL / CONTROLS
FLOW CHARTS
LUNAR MINING PROJECT
GROUP 5 MARCH 11, 1986
FIG. 13(c) DRAWN BY: LA



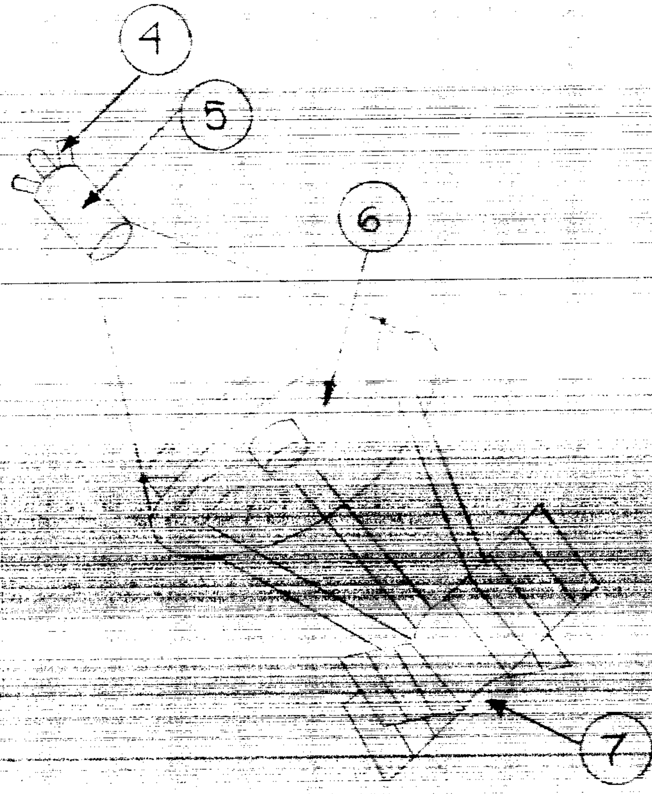
VISUAL / CONTROLS
FLOW CHARTS
LUNAR MINING PROJECT
GROUP 5 MARCH 11, 1986
FIG. 13(d) DRAWN BY: LA

PHOTOVOLTAIC CENTRAL
POWER STATION
100MW LASER



NO.	PART NAME
1	ELECTRIC DISCHARGE LASER SYSTEM (30m DIAMETER TRANSMITTER
2	SOLAR ARRAY (GaAs)
3	HEAT PIPE RADIATORS
4	30m DIAMETER TRANSMITTERS
5	BEAM SPLITTING OPTICS
6	FOCUSED SOLAR REFLECTOR
7	LASER

SOLAR-PUMPED
LASER

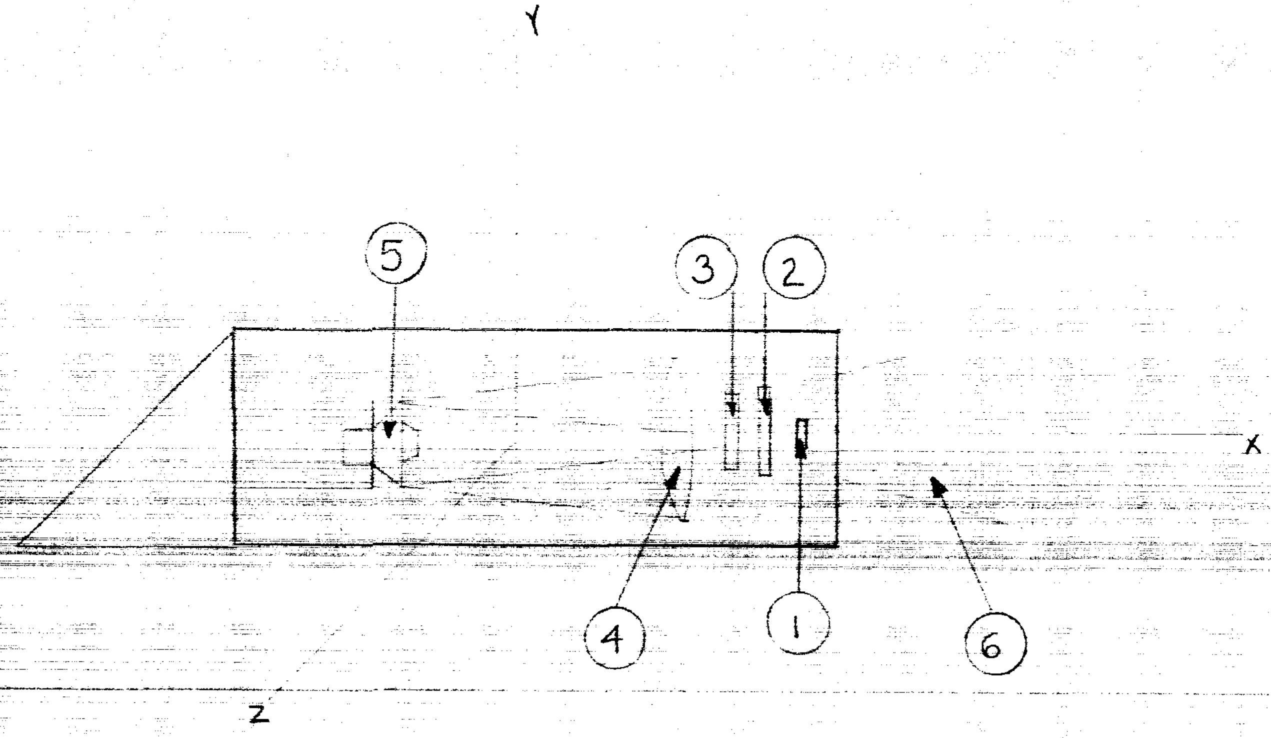


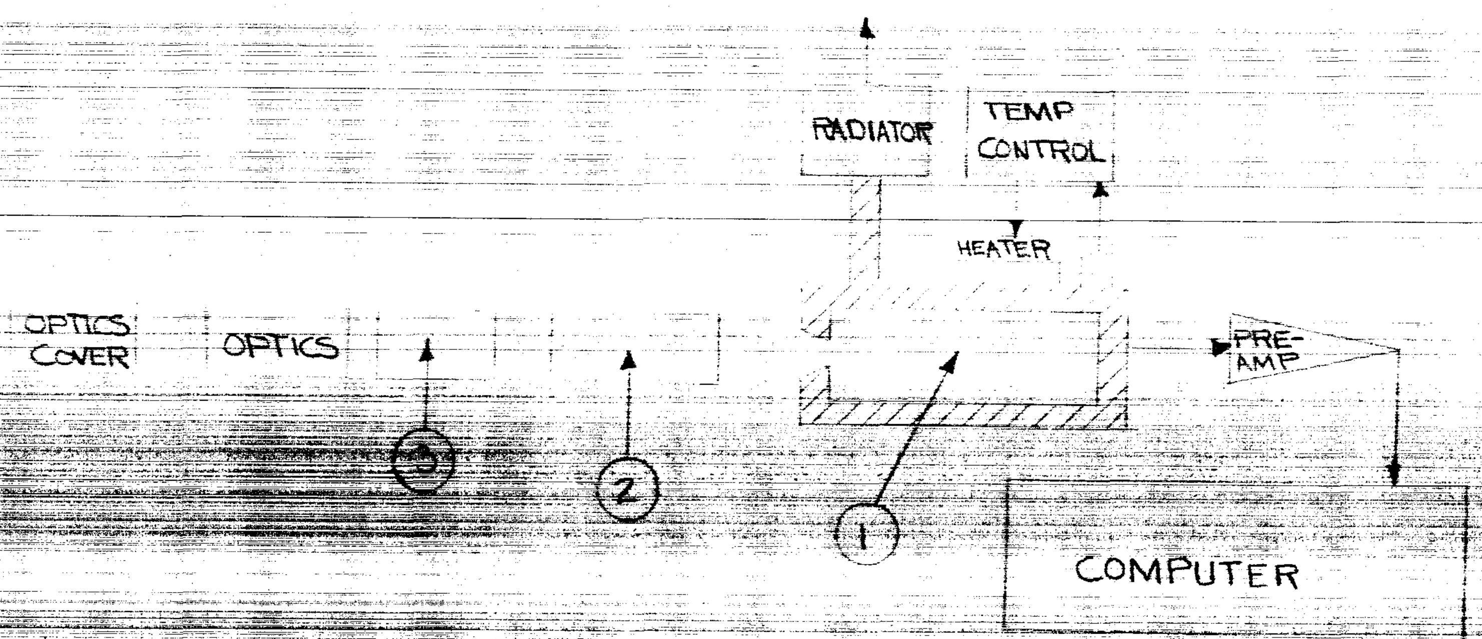
LASER SATELLITES

LUNAR MINING PROJECT

GROUP 5 MARCH 11, 1986

FIG. 13 (e) DRAWN BY: LA





NO.	PART NAME
①	CCD
②	SHUTTER
③	FILTER
④	PRIMARY LENS (MIRROR)
⑤	SECONDARY LENS (MIRROR)
⑥	LENS

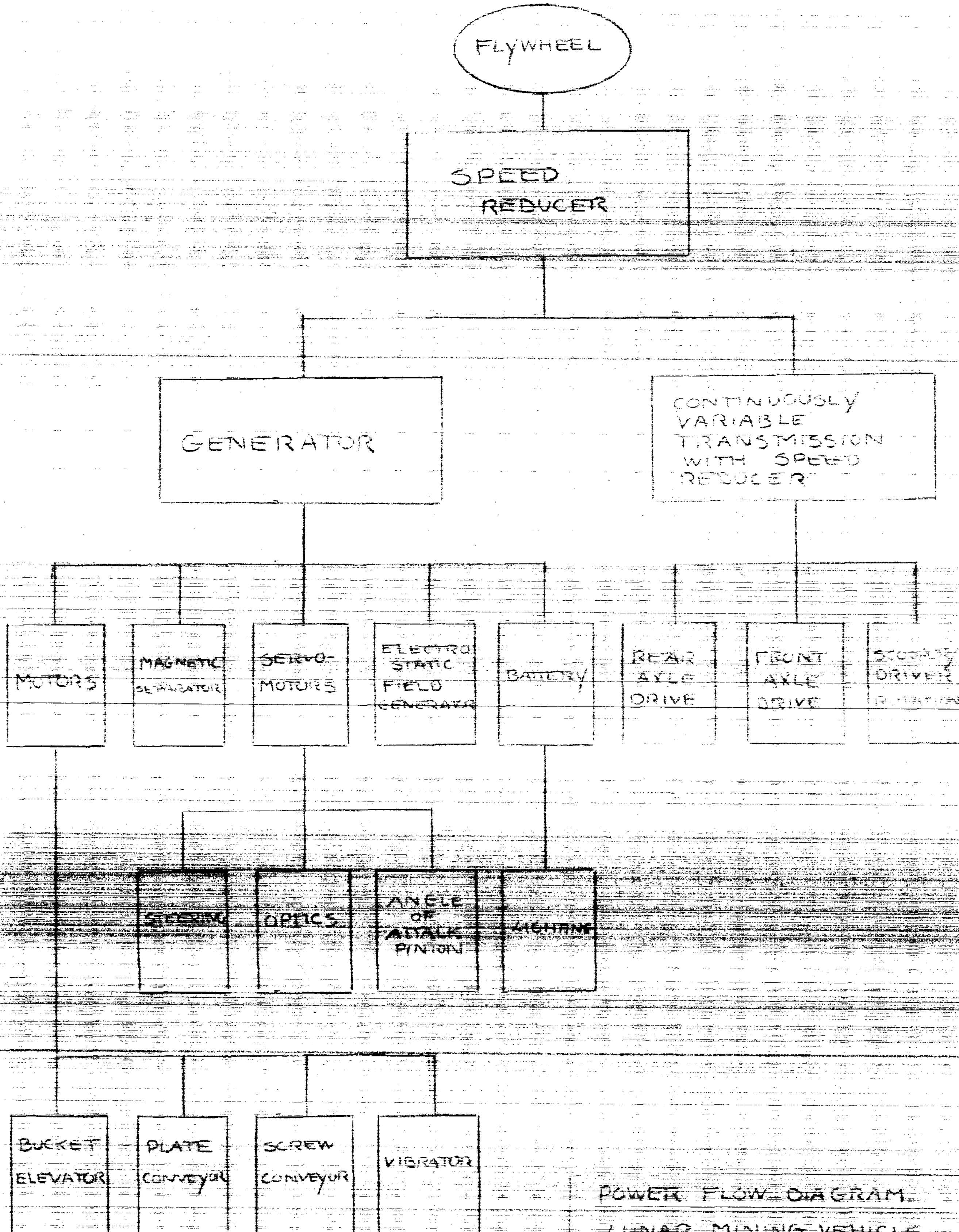
VISUAL / CONTROLS

CAMERA DESCRIPTION

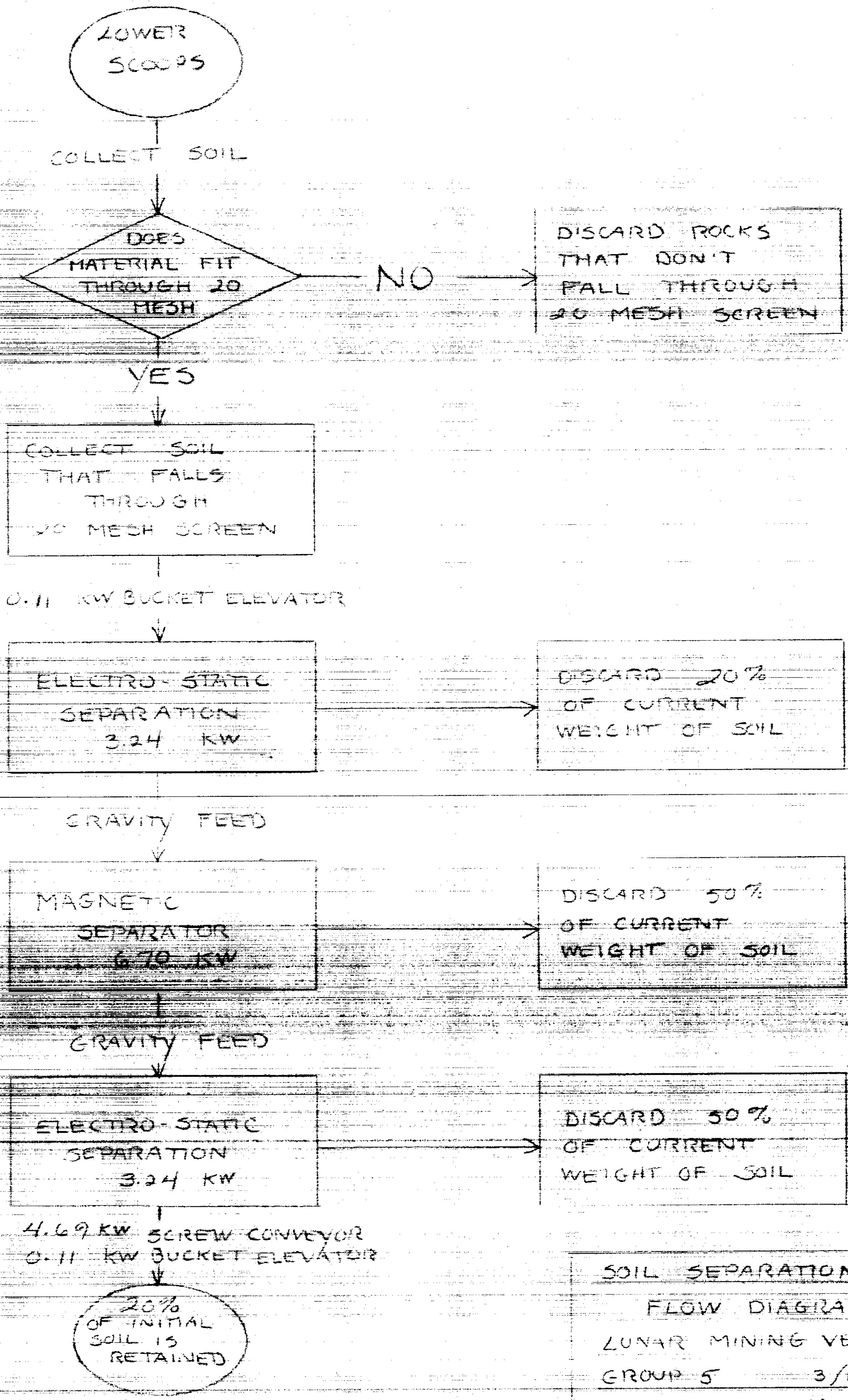
LUNAR MINING PROJECT

GROUP 5 MARCH 11, 1986

FIG. 14 DRAWN BY: LA



POWER FLOW DIAGRAM
LUNAR MINING VEHICLE
GROUP 5
MARCH 11, 1986
FIGURE #15



SOIL SEPARATION
FLOW DIAGRAM
LUNAR MINING VEHICLE
GROUP 5 3/11/86
FIGURE 16

APPENDIX F

VEHICLE MASS ANALYSIS

COMPONENT	MASS IN KG
WHEELS	35
MAGNETIC SEPARATOR	6125
FLYWHEEL	970
AUGER	170
BUCKET BELT / BUCKETS / MOTORS	180
ELECTRO-STATIC SEPARATOR	6030
CUPS FOR SCOOPER/DRIVE	3330
DRIVE TRAIN	
CUP DIFFERENTIAL	90
FRONT AXLE DIFFERENTIAL	70
REAR AXLE DIFFERENTIAL	70
DRIVE SHAFTS	46
CONTINUOUSLY VARIABLE TRANS.	1680
SHELL	16000
MISCELLANEOUS (CAMERA, CONTROLS, ETC.)	1000
	35796 Kg.
	= 78,751 LB.
	= 39.4 SHORT TON

Progress Report
20 January 1986
Group 5
Lunar Mining System

GENERAL

- worked on problem statement development
- studied various constraints peculiar to the lunar environment: harsh lighting, near vacuum atmosphere, low gravity field, long "day" and "night", exorbitant initial transport cost

VISUAL/CONTROL SYSTEMS

- general data acquisition and conceptual review of control systems
- generated flow charts delineating progression from input command to actual physical response
- studied previous unmanned missions (Surveyor, Voyager, Mariner) for their visual system construction
- decided to eliminate <u>in situ</u> operator in favor of remotely controlled vehicle; too many unfavorable constraints to design for

ORE SEPARATION AND BENEFICIATION

- researched lunar surface, soil, geography in NASA reports and numerous books
- discussed conveyor belt and magnetic belt separation method of beneficiating FeO as a continuous process
- the stages of soil separation were outlined and began looking into stages of ore processing that we will be concerned with

MECHANICAL DETAILS

- decided that the digging and moving motions of the mining vehicle must work together; several preliminary designs drawn up to explore these possibilities:
  - a scoop-type front loader that would bury the scoop in the soil in front of the vehicle and pull the vehicle forward to the scoop, forcing the soil into the catcher/bin between them - discounted as not being a good, smooth, continuous process
  - screen-covered augers that would pull the vehicle forward as soil is drawn into the vehicle and separated - good potential
  - paddle-wheel drive that would push the vehicle forward while soil was collected in its "paddles" to be flung into a bin in front of it - would have good traction, but a lot of dust would be kicked up

Progress Report
27 January 1986
Group 5
Lunar Mining System

MOTIVE DRIVE

- developed idea of non-cyclic heat engine and began to investigate further; non-cyclic heat engine would use superheated and supercooled bricks, utilizing thermal extremes and insulation advantages available on the moon
- looked at other power sources for the mobile digger including storage batteries, fuel cells, laser power transmission, and photovoltaic cells

ORE SEPARATION AND BENEFICIATION

- determined two separate ores to be mined on lunar surface - ilmenite and anorthosite
- searched through NASA abstracts for articles on soil mechanics and ore separation
- researched iron, aluminum, titanium processing methods in current terrestrial use

VISUAL/CONTROL SYSTEMS

- visual systems will utilize servomotors - analysis of motors
- researched current robotic visual systems, flow chart for visual system and decision making (AI) - industrial manufacturing robots
- attempt at analyzing vibration and thermal effects on the stability of the cameras

MECHANICAL DETAILS

- discussed and debated relative merits of:
  - (a) totally fixed base with "front-end loaders" (as in Eagle Engineering report)
  - (b) totally mobile finished product processors (as in December, 1985 ME 4182 project)
  - (c) platform processing base transported by mobile rovers
  - (d) hybrid rovers/processors feeding fixed base which will do further processing
- initial thoughts are that option (d) would be optimum: design that incorporates limited processing (to reject, say, 80% if raw ore) with further beneficiation at a fixed base

Progress Report
3 February 1986
Group 5
Lunar Mining System

MOTIVE DRIVE

- compared energy densities of various secondary cells
- continued concept development of the non-cyclic heat engine
- fuel cells appear to be the best "proven" energy density
- heat engine will be very difficult to analyze quantitatively

ORE SEPARATION AND BENEFICIATION

- determined that rover should only contain beneficiation process to reduce soil to high grade ore which would yield substantial savings in transportation to lunar base and in final ore processing

MECHANICAL DETAILS

- auger design was considered for modification into to the finalized driving/collecting mechanism; a bare screw mechanism was discounted as an impractical variation on this design, as it would be difficult to steer and to vary the digging depth
- cement mixer-type digging mechanism was decided on as an auger variation; the outside flute would be turning as it was pushed along in front of the mining cab; the internal screws would be used to move and separate the collected material
- idea of a composite vehicle system was brought up and actively pursued; idea being that there would be individual vehicles for separate functions - a mining vehicle would collect material, a trailer vehicle would act as a mid-point field holding tank, and a cab would pull the trailers and disabled mining vehicles back to the base for unloading and repair; a coupling mechanism would have to be worked out to link the system together - a joint project with group 7 that is developing the cab design
- coupling systems will have to account for the uneven surface of the moon that will affect the connection; it will have to be a system that can be locked into place and then easily disengaged

VISUAL/CONTROL SYSTEMS

- reviewed process of telemetry for transmitting data - eleminated lasers as a possibility; default to fuel cells
- researched power transmission utilizing lasers (direct solar pumped, few conversion components; q-switched, mode locked vs. continuous wave)

Progress Report
2 February 1986
Group 5
Lunar Mining System

MOTIVE DRIVE

- decided to shelve non-cyclic heat engine concept because of complexity and poor expected efficiency
- many different satellite designs researched; best bet would probably have been CO2 or solar pumped laser satellite to beam energy to lunar vehicles on surface; however, because of cost constraints and small angular tolerances decided to table this concept in lieu of other possibilities
- also researched fuel cells as the "tried and tested" method of power generation
- decided to pursue concept of expendable fuel cell "packets" which could be ejected when exhausted for pick-up by group 7's lunar transport
- compiled substantial listing of NASA reports of Apollo LRV to be further explored

ORE SEPARATION AND BENEFICIATION

- found two informative flow charts on ore separation (from ilmenite and anorthosite) which will yield valuable overview of process
- researched soil mechanics science in various journals and papers
- propose use of electrostatic and magnetic separators without presence of fluid media, so as to bypass use of airlocks in the benefication section of the miner
- propose use of primarily electrostatic separators because of savings in weight and energy

MECHANICAL DETAILS

- worked on preliminary design of "front end" for miner; tried to use "styrofoam cup" dual loader concept

GENERAL

- angle of repose would be more acute on the moon's surface than on the earth's surface
- met with group 7 in order to envision proper interface between our mining rover and their dump truck

Progress Report
17 February 1986
Group 5
Lunar Mining System

MECHANICAL DETAILS

- wheel design was narrowed down between wheel and tractor tread method of traction; an aluminum mesh design like those used on Apollo missions on the LRV, would be best as they allow for more deflection on the surface, would have better traction with more weight concentrated on a smaller area, and are lightweight; tractor treads would involve many linkages requiring more lubrication and adding possible breakdown problems
- wheel design was further narrowed by the comparison of two wheel designs; in a NASA study, an open mesh and closed mesh design were contrasted, both meeting NASA's soil mechanics specifications and the incline, speed, and load-bearing requirements for the lunar surface; the closed mesh performed better on loose soil slopes greater than 20 degrees, but since it required more power to operate to overcome elasticity and incurred rips in its fabric, the open mesh wheel was considered the better design; we will continue to further research this design problem in future weeks
- isometric view of machine concept drawn for reference

MOTIVE DRIVE

- continued with research into fuel cell systems; decided on one team member to specialize in this area by doing extensive research into the "mechanics" of fuel cells
- decided storage batteries would be system back up in the event of failure
- discussion of power transmission options available (i.e., continuously variable "gearing", direct-drive electric motors, shaft lubrication)

ORE COLLECTION

- tentatively decided to fix angle of intersection (theta on cup models) according to optimum mining angle
- worked on different linkage arrangements to vary angle of attack of scoopers with respect to horizontal; configuration should naturally lock in place when not being changed
- developed preliminary linear mining speed and volume requirements from initial scooper/driver dimension estimates

GENERAL

- for estimation purposes we have assumed four fully operable miners on the lunar surface

VISUAL/CONTROL SYSTEMS

- idea for transposing material from initial intake to beneficiation
- positioning of cameras, number of cameras, and function
- more detail of depth perception, motors, structures of cameras

ORE SEPARATION AND BENEFICIATION

- decided that only soil less than 1 cm would be processed further than the digging mechanism
- determined that the beneficiaton process would involve one electrostatic separator and one drum-type magnetic separator
- determined to use an electrostatic separator with an alternating curvilinear electric field and a vibratory conveyor for triboelectrification purposes

Progress Report
24 February 1986
Group 5
Lunar Mining System

MECHANICAL DESIGN

- pinpointed design specifications and power requirements for screw conveyor within vehicle from the VSMF catalog
- designed flywheel that will deliver required power for 5 hours
- studied various continuously variable traction drive transmissions and chose a model from VSMF catalog that should fulfill requirements

MISCELLANEOUS

- angle of repose of a soil was found to be "about the same as the angle of internal friction" of the soil; that value is designated by the slope of tangent line drawn on a Mohr diagram; this value was set by NASA for use in simulated soil tests as 35 degrees plus or minus 4 degrees
- information on non-lubricating bearings was found with factors relating to power consumption
- continuous discharge conveyor elevator designs were investigated through the VSMF catalogs; possibilities include belt and chain driven buckets

ORE SEPARATION AND BENEFICIATION

- sized vibratory conveyors for both electrostatic separators from VSMF and determined to use Carpco double-roll induced magnetic separator
- determined that screw conveyor should not be used for vertical lift to beneficiation process or to holding bin at discharge because at 45-degree angle only 50% efficiency is attained

MATERIAL SELECTION FOR COMPONENTS OF VEHICLE

- investigated vacuum/radiation effects on alloys, ceramics (evaporative effects in vacuum environment, induced thermal stresses, blistering effects, pitting and metallic vapor deposits on optical devices, and changes in mechanical properties)
- material selection made for front scooper/drivers and panels of body

CHARGED-COUPLED DEVICE VS. VIDICON CAMERA TUBE

- benefits of CCD:
    - smaller, lighter, no additional heating elements involved
    - good in very low light and bright light (no burning of image on photosensitive sensor)
    - already has horizontal and veritcal pixels

Progress Report 7
3 March 1986
Group 5
Lunar Mining System

ORE SEPARATION AND BENEFICIATION

- investigated mathematical model of separation process based on fractions of ore and separator efficiency
- defined power requirements for electrostatic separators and magnetic separators
- wrote rough draft

MECHANICAL DESIGN

- evaluated various layout problems in elevation and plan views
- sized all mechanical components
- evaluated speed reducer clutch and differential designs with respect to space-use considerations
- performed design calculations for speed reducers and shafts
- finalized layout of power transmission system and drive train
- developed differential and continuously variable transmission

GENERAL

- compiled various power requirements and compared with flywheel output availability
- continued writing report segments dealing with the drive train

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